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Research Article

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Portal Blood Flow in Cirrhosis of the Liver *

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Summary. Direct measurements of portal flow and pressure in a relatively large number of patients with cirrhosis show a marked reduction in flow associated with a nearly constant plateau of portal pressure. This lack of correlation indicates the complex relationships of resistances in the splanchnic, collateral, and hepatic circuits determining the division of the available splanchnic flow between the portal vein and the collateral pathways. Subtracting the measured portal flow from well-established estimates of total hepatic blood flow in cirrhosis suggests that the hepatic artery contributes more than one-half of the blood perfusing the cirrhotic liver. There was no instance of retrograde portal flow during the preshunt measurements, although such reversal was frequent after side-to-side portacaval anastomosis. Attempting to explain the plateau of portal pressure in the face of an increasing outflow resistance presumably associated with progress of the disease, we postulate that an augmented inflow resistance to the splanchnic chamber reduces splanchnic flow in cirrhosis. End-to-side portacaval anastomosis did not return normal portal flow, although it decreased pressure to accepted control levels. The assumption is that most of the splanchnic blood was flowing through the shunt, leading to a high splanchnic resistance in the immediate postshunt status. If this resistance was previously elevated, as suggested by the plateau of portal pressure, the mechanism responsible for the elevation was not immediately deactivated after the shunt, and the true effect of the operation upon splanchnic flow may not be measurable at such time.

Respiratory oscillations were a significant component of portal flow in cirrhosis before and after portacaval anastomosis, indicating the limitations of any steady state analysis of the circulatory derangement in cirrhosis.

Introduction

Beginning with the original observations of Bradley, Ingelfinger, Groff, and Bradley (1), a body of evidence indicates a significant reduction in total hepatic blood flow in patients with cirrhosis of the liver. We have considerably less information, however, on the relative contribution of the portal vein to the diminished total perfusion of the cirrhotic liver. Redeker, Geller, and Reynolds (2) subtracted total estimated hepatic blood flow before and after end-to-side portacaval anastomosis and found no severe reduction in portal flow. A similar subtraction in one of our previous studies showed opposite results (3). Again, using indirect methods, Grabner (4) estimated a significantly reduced portal contribution in hepatic cirrhosis, whereas Myers (5) calculated this contribution to be as low as 25 to as high as 75% of the total flow.

We have even less information from direct measurements of portal venous flow in cirrhosis.

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Ferguson (6), using an electromagnetic flowmeter, measured a marked reduction in portal flow in 11 patients, whereas Schenk, McDonald, McDonald, and Drapanas (7), with a similar instrument, found no significant differences between the mean portal flow in five patients with cirrhosis and that in their normal control subjects.

In this report we will present the results of direct measurements of portal flow and pressure taken at the operating table before and, less frequently, after portacaval anastomosis in a relatively large series of patients with cirrhosis. Additional measurements included systemic arterial pressure and, in a smaller proportion of the patients, pressure on the hepatic and splanchnic sides of a clamp occluding the portal vein and pressure in the inferior vena cava. Portal flow was also measured in a small normal control group. The results indicate that *1*) there was a severe reduction in portal venous flow in most of these patients with cirrhosis; *2*) in this group of patients, portal pressure remained nearly constant around 30 mm Hg; *3*) throughout the series, patients with approximately the same portal pressures had remarkably different values of portal flow; *4*) in most patients, portal flow failed to return to normal values after the construction of a portacaval anastomosis, even when the return to normal portal pressure indicated a successful shunt; and *5*) respiratory oscillations affected portal flow before and after portacaval anastomosis.

Methods

One hundred sixteen direct measurements of flow and pressure in the portal vein in 85 patients with cirrhosis, 30 of them with associated ascites, comprised the material for this study. Measurements of normal portal flow were taken in six patients without liver disease. A noncannulating flow probe (12.6 or 11 mm i.d.) was positioned around the portal vein between pancreas and hilum of liver and connected to the square wave electromagnetic flowmeter of Denison and Spencer.[1] Temporary downstream occlusion of the portal vein rendered zero flow base line. Measurements were considered unsatisfactory and discarded if the probe angulated or compressed the portal vein and elevated portal pressure, if electrical artifacts resulted from close proximity of the occluding clamp to the magnetic field generated by the probe, or if an unsteady base line could not be readily corrected. Thirty-one patients had additional satisfactory measurements after portacaval anastomosis; 18 of them had an end-to-side shunt, and flow was measured in the portal vein immediately before the point of anastomosis to the vena cava. The remaining 13 patients had a side-to-side anastomosis, and flow was measured in the hepatic limb of the shunt. Probes were calibrated against flows covering the entire range of predictable values (gross errors in our early measurements resulted from using probe factors derived from the area under the curve corresponding to the injection of a single measured amount of blood). Flow measurements were converted to milliliters per minute per kilogram of body weight. Twenty-six patients had additional measurements of pressure on the hepatic and splanchnic sides of a clamp occluding the portal vein, and seven had pressure measurements in the inferior vena cava. Pressures were measured with water manometers or with differential transformer transducers [2] and referred to a base line corresponding to the anterior aspect of the upper lumbar vertebrae (8, 9).

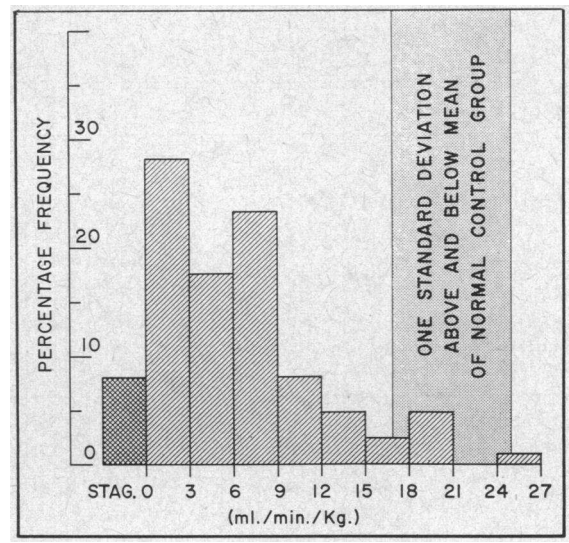

FIG. 1. FREQUENCY DISTRIBUTION OF PORTAL VENOUS FLOW IN 85 PATIENTS WITH CIRRHOSIS (SQUARE WAVE ELECTROMAGNETIC FLOWMETER). For convenience, the bar corresponding to the patients who had no flow in the portal vein (stagnant flow) has been placed to the left of the zero on the abscissa scale. This does not represent negative values, which, in this case, could be interpreted as retrograde flows.

Results

Portal flow in normal subjects. Mean portal flow in six normal control subjects was 20.9 ± 4.1 (SD) ml per minute per kg (Table I).

Portal flow and pressures in cirrhosis before portacaval anastomosis. Portal flow was signifi-

[1] Carolina Medical Electronics, Winston-Salem, N. C.

[2] Sanborn model 268 pressure transducers.

TABLE I

Volume flow in the portal vein in six normal control subjects

Patient	Flow	Weight
	ml/min/kg	*kg*
1	13.4	65.0
2	19.1	73.9
3	20.7	56.0
4	22.6	59.5
5	23.5	64.5
6	26.3	56.8
Mean volume flow	20.9	
Standard deviation of the mean	±4.1	
Standard error of the mean	1.6	

cantly reduced in most of the 85 patients with cirrhosis, 6.5 ± 5.6 (SD) ml per minute per kg (Table II and Figure 1). Almost 93% of the patients had flows smaller than 1 SD below the mean of the control group, and almost one-half had flows less than one-fifth the mean normal value. Seven patients had stagnant flow, which showed only a slight to-and-fro motion during respiration. There was no instance of retrograde flow in the portal vein.

Mean portal pressure in patients with cirrhosis was 29.7 ± 4.1 (SD) mm Hg. There was no linear correlation between pressure and flow in the portal vein (Figure 2). Portal pressure in the hepatic (cephalic) side of a clamp occluding the portal vein in 26 patients averaged 23.9 ± 5.3 (SD) mm Hg (Table III). Portal pressure on the splanchnic (caudal) side of the clamp had a mean value of 34.9 ± 5.7 (SD) mm Hg. In one

TABLE II

Grouped values of portal flow with ungrouped values of portal pressure and body weight in 85 patients with cirrhosis

Patient	Ascites	Portal flow	Portal pressure	Body weight*
		ml/min/kg	*mm Hg*	*kg*
23	+	0	30.0	49.0
24	+	0	33.5	40.3
38	+	0	33.1	56.8
32	+	0	33.1	58.1
45	+	0	23.1	104.2
56	+	0	26.9	66.8
70	+	0	23.1	67.5
68	−	0.6	34.6	79.4
22	−	0.8	33.1	61.7
67	+	1.0	31.5	78.0
73	−	1.2	29.2	102.7
74	−	1.3	37.7	77.7
25	+	1.4	24.6	51.0
69	+	1.5	22.3	68.0
64	−	1.5	31.5	59.9
21	−	1.6	26.1	82.5
28	−	1.7	28.5	67.0
50	−	1.8	21.9	84.4
52	−	1.9	32.3	78.2
62	+	1.9	38.5	56.0
26	+	2.0	25.4	57.7
81	−	2.1	37.3	47.0
20	−	2.2	33.1	72.7
40	−	2.2	26.5	79.4
29	+	2.4	28.1	79.8
18	+	2.5	26.9	61.3
35	+	2.5	31.5	63.1
39	−	2.5	30.0	57.6
63	−	2.5	26.9	91.2
44	−	2.6	31.5	72.1
82	+	2.8	30.8	89.0
19	−	3.0	31.5	64.4
41	−	3.1	32.7	63.1
72	−	3.1	29.2	63.0
17	−	3.2	37.7	81.8
61	+	3.2	29.5	60.0
37	−	4.0	28.1	78.2
66	−	4.3	28.8	56.2
57	−	4.4	24.6	54.5
30	−	4.5	29.2	75.9
10	−	4.6	34.6	61.8
11	−	5.2	30.8	70.0
27	+	5.2	23.1	42.4
80	−	5.7	37.3	113.0
43	−	5.8	18.8	72.1
76	+	5.8	26.1	65.0
9	−	6.6	33.1	50.0
33	+	6.8	30.8	61.8
59	−	6.8	35.4	77.1
77	+	7.1	30.8	67.0
42	−	7.2	27.7	81.8
47	+	7.2	34.6	58.5
49	+	7.3	33.8	64.4
2	−	7.5	26.9	77.4
84	−	7.6	25.8	49.0
55	+	7.7	34.6	60.8
75	+	7.9	26.1	60.0
14	−	8.0	28.5	50.4
79	+	8.0	24.6	53.0
15	−	8.4	28.8	64.4
8	−	8.7	25.0	66.4
13	−	8.7	27.3	70.0
54	−	8.8	23.1	49.9
1	−	8.8	32.3	74.3
85	+	8.9	30.0	58.6
58	−	9.0	28.1	57.2
6	−	10.7		74.0
71	−	10.9	25.4	71.7
34	−	11.2	28.5	63.1
46	−	11.2	32.3	74.0
48	−	11.3	30.0	59.0
4	−	11.6	32.3	84.0
65	−	12.0	30.8	46.7
78	−	12.8	28.1	72.0
83	−	13.3	30.8	75.0
12	−	13.5	21.9	103.0
16	−	14.6	32.7	43.1
36	−	15.0	35.8	104.5
3	+	16.1	31.5	50.6
51	−	17.8	29.2	55.0
5	+	18.1	27.7	71.3
31	+	20.1	34.2	55.6
60	−	20.6	28.1	55.4
53	−	20.8	30.0	62.1
7	−	25.5	35.4	66.4
All patients				
Mean		6.5	29.7	67.4
SD		± 5.6	± 4.1	± 14.4
SE		0.61	0.45	1.6
55 patients free of ascites				
Mean		7.4	29.9	69.8
SD		± 5.3	± 4.1	± 15.0
SE		0.7	0.5	2.0
30 patients with ascites				
Mean		4.9	29.3	62.5
SD		± 5.3	± 4.1	± 12.6
SE		0.9	0.7	2.3
p value for differences		0.025	0.26	0.009

* Only "dry weights" were used for the patients with ascites.

patient, the hepatic and splanchnic occluded pressures did not differ from the unoccluded pressures, and there was no flow in the portal vein (Patient 23 in Table III). In the other three patients with stagnant flow who had measurements of occluded pressures, the difference between "unoccluded" and "hepatic occluded" pressures was small, averaging only 1.8 mm Hg. In the remaining 22 patients, however, the difference between these two pressure measurements showed no correlation with the magnitude of the portal flow. Pressure in the inferior vena cava was measured in seven patients and averaged 8.6 mm Hg, with a range of 6.6 to 11.7 mm Hg (Table IV). Systemic arterial pressure was in the normal range in all patients, averaging a mean of 98 mm Hg.

TABLE III

Values of occluded portal venous pressures in 26 patients with cirrhosis (grouped by their portal flow values)

Patient	Ascites	Portal pressure (unoccluded)	Hepatic pressure (occluded)*	Splanchnic pressure (occluded)†
		mm Hg	*mm Hg*	*mm Hg*
23	+	30.0	30.0	30.0
24	+	33.5	31.1	35.0
38	+	33.1	31.5	38.4
45	+	23.1	21.5	24.5
22	−	33.1	28.4	46.2
73	−	29.2	22.3	33.0
74	−	36.7	30.8	40.0
25	+	24.6	20.0	26.1
21	−	26.1	18.4	32.8
50	−	21.9	21.9	31.9
26	+	25.4	14.6	36.1
81	−	36.3	33.0	41.5
40	−	26.5	23.8	38.8
39	−	30.0	28.1	35.8
41	−	32.7	28.8	37.1
72	−	29.2	26.7	31.5
27	+	23.1	16.9	27.6
43	−	18.8	17.3	24.2
76	+	26.1	17.1	29.9
42	−	27.7	20.7	29.2
58	−	28.1	16.5	33.4
34	−	28.5	22.3	32.1
48	−	30.0	20.3	34.2
65	−	30.8	26.6	46.2
83	−	30.8	25.4	35.0
53	−	30.0	27.6	38.4
All patients				
Mean		28.7	23.9	34.9
SD		± 4.4	± 5.3	± 5.7
SE		0.8	1.0	0.6
Patients free of ascites				
Mean		29.2	24.3	35.6
SD		± 4.2	± 4.6	± 5.4
SE		0.9	1.1	1.2
Patients with ascites				
Mean		27.3	22.8	30.9
SD		± 3.9	± 6.5	± 4.7
SE		1.4	2.3	1.7
p values for differences between ascites and nonascites		0.3	0.5	0.1

* Pressure on the hepatic (cephalic) side of a clamp occluding the portal vein.

† Pressure on the splanchnic (caudal) side of a clamp occluding the portal vein.

TABLE IV

Values of pressure in the inferior vena cava in seven patients with cirrhosis (with associated values of portal flow and pressure)

Patient	Ascites	Inferior vena caval pressure	Portal pressure	Portal flow
		mm Hg	*mm Hg*	*ml/min/kg*
52	−	6.6	32.3	1.9
27	+	7.3	23.1	5.2
15	−	7.3	28.8	8.4
25	+	8.5	24.6	1.4
54	−	8.8	23.1	8.8
39	−	10.3	30.0	2.5
34	−	11.7	28.5	11.2
Average		8.6	27.2	5.6

Measurements of flow and pressure in relation to presence or absence of ascites. Mean portal flow was 7.4 ± 5.3 (SD) ml per minute per kg in 55 patients without ascites and 4.9 ± 5.3 (SD) ml per minute per kg in 30 patients with associated ascites. The difference was statistically significant at the level of 0.05 but not at the 0.02 level (Ta-

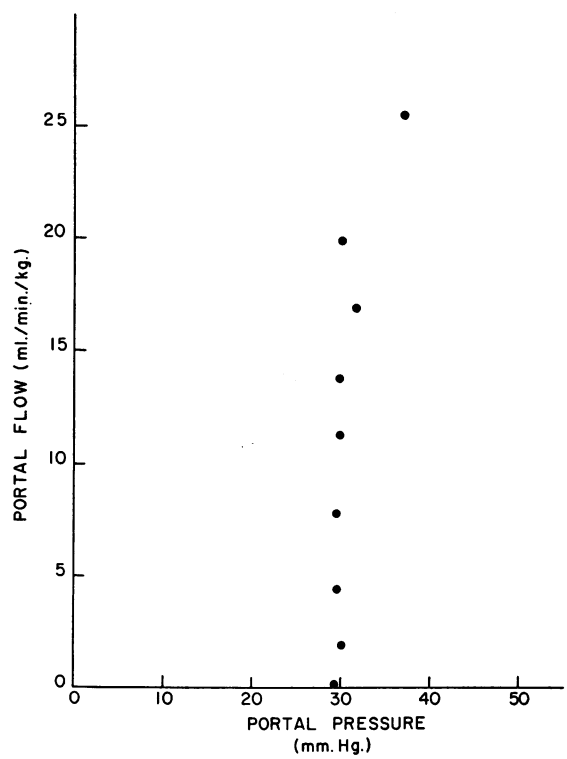

FIG. 2. SIMULTANEOUS VALUES OF FLOW AND PRESSURE IN THE PORTAL VEIN OF 85 PATIENTS WITH CIRRHOSIS. Dots represent mean pressures for the groups in the frequency distribution of flows shown in Figure 1.

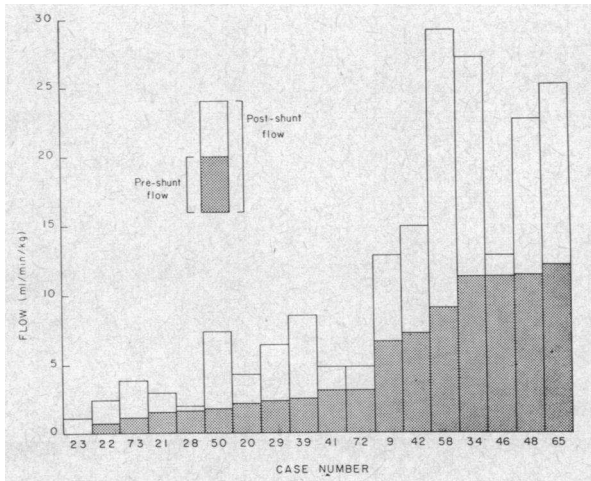

FIG. 3. INCREASE IN PORTAL FLOW AFTER END-TO-SIDE PORTACAVAL ANASTOMOSIS IN 18 PATIENTS.

ble II). Mean portal pressure in patients with ascites was 29.3 ± 4.1 (SD) mm Hg and 29.9 ± 4.1 (SD) mm Hg in patients without ascites. The difference was not statistically significant, $p > 0.9$ (Table II). Occluded pressures were measured in 18 patients free of ascites and in 8 patients with associated ascites. The hepatic occluded pressure averaged 22.8 ± 6.5 (SD) mm Hg for the first group and 24.3 ± 4.6 (SD) mm Hg for the second group. The difference was not statistically significant ($p = 0.5$). The gradient between the unoccluded portal pressure and the hepatic occluded pressure averaged 4.5 ± 3.6 (SD) mm Hg for the nonascitic group and 4.9 ± 2.9 (SD) mm Hg for the ascitic group. Again, the difference was not statistically significant, with $p = 0.8$. Pressure in the inferior vena cava was 7.3 and 8.5 mm Hg in two patients with ascites, and it averaged 8.9 mm Hg in five patients free of ascites (Table IV).

Flow and pressures after end-to-side portacaval anastomosis. Flow in the portal vein after its anastomosis to the vena cava was approximately double the preshunt flow. However, there was a certain proportion between pre- and postshunt flows, with small flows being followed by relatively small flows and larger flows by correspondingly larger flows (Table V). Although, in both instances, the increment may have been 100% or more over the initial flow (Figure 3), postshunt portal flow averaged only 10.8 ± 9 (SD) ml per minute per kg and failed to approach the values in the control group in 14 of the 18 patients. By contrast, portal pressure generally returned to normal values and averaged 13.6 ± 3.1 (SD) mm Hg (Table V). Systemic arterial pres-

TABLE V

Pre- and postshunt measurements in 18 patients with cirrhosis*

Patient	Preshunt portal flow	Postshunt portal flow	Preshunt portal pressure	Postshunt portal pressure	Preshunt arterial pressure	Postshunt arterial pressure
	ml/min/kg	*ml/min/kg*	*mm Hg*	*mm Hg*	*mm Hg*	*mm Hg*
23	0.0	1.2	30.0	15.2	100	95
22	0.8	2.5	33.1	10.2	110	115
73	1.2	3.9	29.2	11.0	117.5	110
21	1.6	3.0	26.1	17.6	100	85
28	1.7	2.0	28.5	7.3	97.5	97.5
50	1.8	7.4	21.9	11.0	80	102.5
20	2.2	4.3	33.1	21.3	102.5	110
29	2.4	6.4	28.1	13.2	115	115
39	2.5	8.5	30.0	12.1	85	90
41	3.1	4.8	32.7	12.5	115	92.5
72	3.1	4.8	29.2	11.0	105	100
9	6.6	12.8	33.1	13.9	75	62.5
42	7.2	14.9	27.7	12.5	100	105
58	9.0	29.0	28.1	15.4	90	102.5
34	11.2	27.0	28.5	13.9	95	90
46	11.2	12.7	32.3	17.4	82.5	82.5
48	11.3	22.5	30.0	15.1	100	100
65	12.0	26.0	30.8	13.9	105	97.5
Mean	4.9	10.8	29.6	13.6	98.6	97.4
SD	±4.1	±9.1	±2.8	±3.1	±6.4	±6.9
SE	0.9	2.1	0.6	0.7	1.5	1.6

* End-to-side portacaval anastomosis.

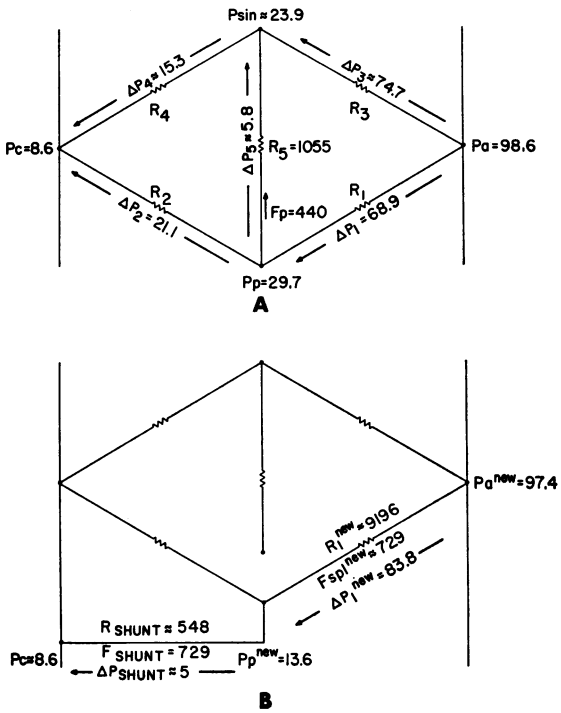

FIG. 4. CALCULATIONS AND APPROXIMATIONS OF SOME OF THE VARIABLES AND PARAMETERS OF BRADLEY'S WHEATSTONE BRIDGE MODEL FOR THE SPLANCHNIC, COLLATERAL, AND HEPATIC CIRCUITS IN CIRRHOSIS. A, before portacaval anastomosis; B, after end-to-side portacaval shunt. R_1 = splanchnic resistance; R_2 = collateral resistance; R_3 = hepatic arteriolar resistance; R_4 = postsinusoidal resistance; R_5 = portal venular resistance. P_a = systemic arterial pressure; P_p = portal pressure; P_{sin} = sinusoidal pressure approximated from hepatic occluded pressure (see Discussion); P_c = inferior vena caval pressure; ΔP = gradients of pressure. F_p = portal flow in milliliters per minute; F_{SHUNT} = flow through the shunt; F_{spl}^{new} = splanchnic flow after the shunt, assuming that $F_{spl}^{new} \approx F_{SHUNT}$ if $R_{SHUNT} \ll R_2$. All pressures and pressure gradients are in millimeters Hg, resistance in dynes-second-centimeter^{-5} (from $\Delta P \times 80{,}000/F$, milliliters per minute).

sure had a mean value of 98.6 ± 6.4 (SD) mm Hg at the time of the preshunt measurements of portal flow and pressure, and a mean value of 97.4 ± 6.9 (SD) mm Hg during the postshunt measurements.

Measurements after side-to-side portacaval anastomosis. Reasonably satisfactory measurements in the hepatic limb of the anastomosis could be taken in only 13 patients. In eight, hepatic blood flowed in a retrograde manner from the liver to the vena cava (range 0.8 to 12.5 ml per minute per kg). In one patient, the flow was stagnant and only a to-and-fro motion was recorded during the respiratory cycle. In four patients, a rather small flow of blood toward the liver was measured (range 1.9 to 4.6 ml per minute per kg).

Calculations and approximations. Measurements of flow and pressure gave approximations to the values of some of the variables and parameters of the Wheatstone bridge model proposed by Bradley (10) for the hepatic and splanchnic circuits. Figure 4, A, shows the estimates for these values before the shunt, and Figure 4, B, presents those for the values after the end-to-side portacaval anastomosis.

Effect of respiration. Flow in the portal vein showed oscillations synchronous with the respiratory cycle. In control subjects and in the few patients with cirrhosis whose portal flow remained within normal ranges, the oscillations had a relative magnitude approximating 20% of the total flow (Figure 5, A and B). With smaller mean flows, the absolute value of the oscillations did not change overtly, but their relative magnitude increased as a fraction of the mean value to reach 80 or even 100% when the flow was very small (Figure 5, C to F).

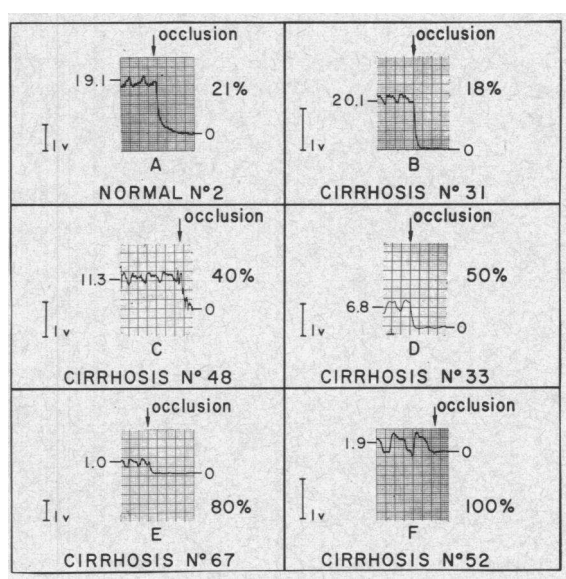

FIG. 5. RESPIRATORY OSCILLATIONS IN PORTAL FLOW IN ONE NORMAL CONTROL SUBJECT AND IN FIVE PATIENTS WITH CIRRHOSIS. From left to right: calibration signal, mean flow in milliliters per minute per kilogram body weight, and relative magnitude of oscillations in per cent of total flow.

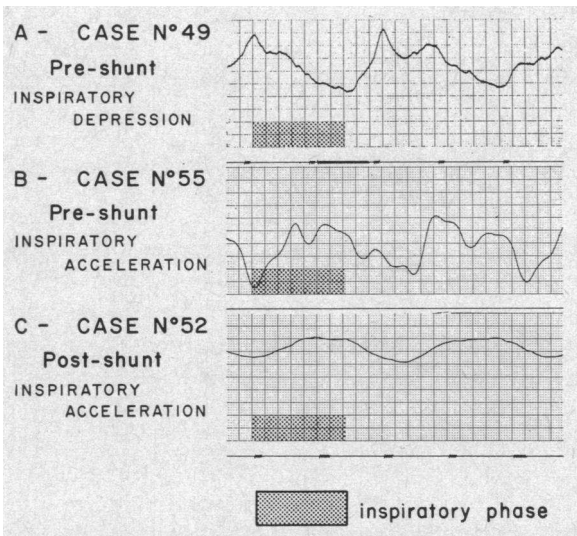

FIG. 6. OSCILLATIONS IN PORTAL FLOW IN THREE PATIENTS WITH CIRRHOSIS MAGNIFIED BY APPROXIMATELY THE SAME INSTRUMENTAL GAIN. A: inspiratory depression in flow, as in normal subjects; B: in this patient, flow accelerated instead of decelerating during each inspiration; C: after end-to-side portacaval shunt, flow accelerates during inspiration.

Inspiration depressed portal flow in control subjects and in some patients with cirrhosis (Figure 6, A), whereas it accelerated flow in other patients (Figure 6, B). After end-to-side portacaval anastomosis, inspiration always accelerated portal flow (Figure 6, C). In eight patients who had retrograde flow (away from the liver) in the hepatic limb of a side-to-side portacaval anastomosis, inspiration always accelerated the flow, and the oscillations represented from 30 to 100% of the total flow (Figure 7, A and B). In four patients with slight forward flow in the hepatic limb of the shunt, inspiration decreased flow in one (Figure 7, C) and accelerated flow in another. Unsatisfactory identifying markers made it impossible to establish the effect in the other two.

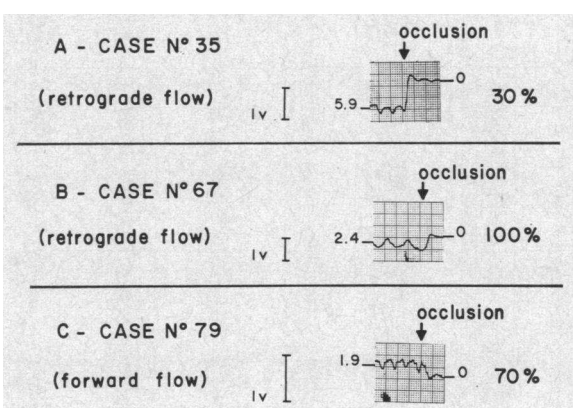

FIG. 7. RECORDINGS OF FLOW IN THE HEPATIC LIMB OF A SIDE-TO-SIDE PORTACAVAL ANASTOMOSIS. From left to right: calibration signal, mean flow in milliliters per minute per kilogram body weight, and relative magnitude of oscillations in per cent of total flow. Recordings A and B show retrograde flow (away from the liver), and recording C shows forward flow (toward the liver).

Discussion

Measurements at the operating table can be affected by anesthesia, laparotomy, technical artifacts, and even undetected changes in blood volume and cardiac output. Therefore, our absolute values should not be taken to reflect accurately individual changes, but rather as general statements of broad tendencies for circulatory adjustments in cirrhosis.

Our direct measurements of 6.5 ml per minute per kg (or approximately 440 ml per minute) indicate a severe reduction in portal venous flow. Occasionally, flow was so small as to explain the tendency of cirrhotic patients to develop secondary portal venous thrombosis. The measurements also suggest that the hepatic artery contributes the larger portion of the blood that perfuses the cirrhotic liver, because the original observations of Bradley and associates (1), recently validated by Grabner in 81 patients (4), give an estimate of 1,000 ml per minute for total hepatic blood flow in cirrhosis. Since none of our measurements showed retrograde flow in the portal vein, it seems that the incidence of this phenomenon must be very small, if it occurs at all.

The statistically borderline difference in portal flow between patients with and without ascites may relate this complication to an advanced stage of the disease, where a more profound circulatory derangement further impairs hepatic perfusion with splanchnic blood.[3] However, our findings should not lead to the a priori conclusion that cirrhotic ascites results from simple hemodynamic changes, a view favored by some on the basis of the experimental production of ascites in the laboratory animal. Note that there were no statistically signifi-

[3] Note that the seven patients with stagnant portal flow had ascites.

cant differences in portal pressure or in any gradient of pressure.

Concerning the nearly constant portal pressure, which averaged approximately 30 mm Hg, it is of interest that Ferguson's direct measurements in 48 patients show an almost identical value of 30.1 mm Hg (6). Because this may indicate some form of limiting condition in the circulatory disorder of cirrhosis, we re-examined the values of splenic pulp pressure in two of our previous studies including 203 patients subdivided according to a gross splenoportographic estimation of cirrhotic involvement (11, 12). In the more advanced stages, which involved the same type of patients as our present series of direct measurements, splenic pulp pressure reached a mean value of 31.5 mm Hg. All these observations may indicate that, after a period of progressive increase, portal pressure reaches a plateau of approximately 30 mm Hg. Any speculation concerning this plateau should consider the ratio of inflow to outflow resistances in the splanchnic venous chamber as primary determinant for its intravascular pressure (Bradley, 10; Selkurt and Rothe, 13). In advanced cirrhosis, total outflow resistance for the splanchnic chamber is given by the combined resistances of the hepatic and collateral beds. Because all evidence points to unrelenting distortion and compression of the intrahepatic vasculature, a constant portal pressure cannot be thought to result from a stabilized transhepatic resistance. Also, it does not seem plausible that total outflow resistance might be kept indefinitely constant by continuous recruiting of new collateral beds with their resistance parallel to a progressively increasing transhepatic resistance. Therefore, an elevated but constant portal pressure strongly suggests an increased resistance to the inflow of the splanchnic chamber. Selkurt and Johnson (14) have shown increased resistance to flow through the intestine after experimentally elevating portal pressure by impairing portal outflow. With a normal arterial pressure, as observed in our patients, such an increase in resistance would result in a diminished splanchnic flow.

Measurements of pressure on the hepatic side of a clamp occluding the portal vein have been thought to reflect an increase in intrahepatic portal pressure transmitted through arteriovenous shunts between presinusoidal branches of the hepatic artery and presinusoidal portal venules, a concept based on the histological demonstration that such communications become abundant in cirrhosis (Child and Donovan, 15). Recent simultaneous measurements in dogs by Price, McFate, and Shaw (16) indicate that when the portal vein is occluded, wedged hepatic venous pressure and portal pressure on the cephalic side of the occlusion become the same, and that both very closely approximate sinusoidal pressure. They also indicated that arteriovenous communications need not be a significant determinant for changes in the occluded portal pressure. Bradley (10) believes that arteriovenous anastomoses may be more important in regulating the local distribution of flows than in affecting the dynamics of total flow through the liver. Our measurements of pressure on the cephalic side of the occluded portal vein show a mean value of 23.9 mm Hg, which approaches Grabner's mean value of 21.6 mm Hg for wedged hepatic venous pressure in 81 patients with cirrhosis (4), again indicating that sinusoidal pressure was probably the quantity being measured in both cases. Finally, our estimate for mean inferior caval pressure of 8.6 mm Hg based on only seven measurements is almost identical to the average of 8.9 mm Hg directly measured during operation by Ferguson (6) in 48 patients.

The lack of correlation between portal pressure and flow is one more indication of the complex relationships of resistances and implied pressure gradients determining the flows in the hepatic, collateral, and splanchnic circuits of patients with cirrhosis. Bradley's Wheatstone bridge model of these resistive conditions (Figure 4, A) shows that the amount of blood entering the liver through the portal vein depends not only on the splanchnic resistance, but also on the division of the resulting splanchnic flow between the portal vein and the portal–systemic collateral bed. The complexity of the relationships that determine such a flow division ratio can be appreciated from the fundamental mathematical description of the bridge (Smythe, 17), if one derives the ratio of portal flow to splanchnic flow:

$$\frac{F_p}{F_{sp}} = \left(\frac{R_3}{R_4} - \frac{R_1}{R_2}\right)\left(\frac{R_2}{R_5 + R_1 + R_3 + R_3R_5/R_4}\right),$$

where F_p = portal flow, F_{sp} = splanchnic flow, R_1 = splanchnic resistance, R_2 = collateral re-

sistance, R_3 = hepatic arteriolar resistance, R_4 = postsinusoidal venular resistance, and R_5 = portal venular resistance.

Although presently available data are not sufficient to provide a numerical solution for this equation, its derivation is useful to show how the flow division ratio is simultaneously influenced by all the resistances in the circuits and particularly by the imbalance of the bridge, represented by the term in the left parentheses.

After end–to–side portacaval anastomosis, portal flow regularly increased but failed to return to normal values in most patients. Since the elevated portal pressure always decreased to normal, indicating a technically successful shunt, it is unlikely that portal flow was small because a portion of splanchnic blood continued to flow through the collateral bed. If it is assumed that caval pressure did not change significantly, the estimated resistance of the shunt must have been very small (Figure 4, B), suggesting that most of the splanchnic blood should flow through the portal vein into the vena cava. Again, since the outlet resistance primarily affects the pressure, whereas flow depends more directly on the input resistance, our findings strongly suggest a high splanchnic resistance immediately after the shunt. Because there is no reason to believe that construction of the shunt would raise the splanchnic resistance, it is plausible that the resistance was already elevated before the shunt and that the mechanism responsible for the elevation is not immediately deactivated after the shunt. Actually, the plateau of portal pressure already had pointed toward such an increment in preshunt splanchnic resistance. If this is true, the postshunt augmentation in portal flow may simply represent rerouting of splanchnic blood previously diverted through the collateral bed, with the true effect of the shunt upon splanchnic flow not being measurable immediately after the shunt.

The effect of respiration on portal flow indicates the limitations of any steady state analysis of the circulatory derangement in cirrhosis. Using the method of intraparenchymal deposition of contrast medium, we have previously reported that in patients with cirrhosis hepatic outflow increases, instead of decreases, during inspiration (18). The present direct measurements of hepatic inflow confirm these findings. If compression by the descending diaphragm depresses flow in the normally elastic liver (Brauer, 19), such an effect may not be readily induced in the hardened fibrous cirrhotic liver. In the absence of mechanical collapse, the normal inspiratory increment in the gradient for venous return should accelerate flow through the hepatic vasculature, now resembling a circuit of rigid tubes more than a collapsible system. Unfortunately, we did not mark the respiratory cycle in our early recordings and cannot estimate the incidence of this phenomenon. Inspiratory acceleration of splanchnic flow after end–to–side portacaval shunt and of hepatic flow after side–to–side anastomosis again suggests the significant effect of an oscillatory pressure gradient. In some patients, all the blood movement was represented by the oscillations in flow.

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