Measurement of mesenteric blood flow by duplex scanning

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Ultrasonic imaging combined with a pulsed Doppler unit (duplex scanning) allows the noninvasive assessment of blood flow of the superior mesenteric artery. The changes in mesenteric blood flow associated with a standardized (1000 kcal) food load were measured and the results were compared with blood flow of the left common carotid artery. Twenty healthy subjects (aged 30.1 ± 5 years) were studied fasting (12.4 ± 2.6 hours' duration) and six times with a 15-minute interval after the test meal. The diameters of the superior mesenteric artery (0.60 ± 0.09 mm) and of the common carotid artery (0.61 ± 0.05 mm) were measured from the B-mode image. The Doppler frequency spectra were used to determine peak systolic, late systolic, and end-diastolic velocity and to compute the mean velocity. Although the flow parameters of the common carotid artery were virtually unaffected by food intake, a steep increase in mesenteric blood flow velocity and volume flow was observed. At rest, blood flow through the mesenteric artery was 6.3 ± 2.6 ml/sec and 9.5 ± 2.1 ml/sec in the carotid artery. After the test meal, mesenteric artery blood flow increased significantly ($p < 0.0001$) and reached maximal hyperemia (20.3 ± 7.4 ml/sec) after 45 minutes. The measurement of mesenteric blood flow before and after a test meal characterizes intestinal hemodynamics and should be suitable to evaluate ischemic disease and other disorders that lead to changes of mesenteric blood flow. (J VASC SURG 1986; 3:462-9.)

Investigation of the circulatory dynamics in the human intestine has been limited mainly by the fact that the measurement of arterial blood flow to the gut is not feasible by noninvasive techniques. Our knowledge of the intestinal circulation is derived largely from experimental studies in animals. Surgically implanted electromagnetic flowmeters[1,2] and the dye dilution techniques requiring the placement of catheters[3,4] have been used to measure splanchnic blood flow.

It is generally assumed that arterial flow to the intestine is modified during digestion of food.[5-7] The investigations carried out on animals[3,4,8-12] and the few reports on human beings[13-17] describe an increased blood flow to the gut after a food load. Considerable variations between experiments and between the species studied were found. Little is known about the mechanisms governing alterations in the human splanchnic blood flow under different physiologic conditions and in response to disease.

Recently the use of duplex scanning for the noninvasive diagnosis of intestinal angina has been reported in a preliminary study.[18] Ultrasonic duplex scanning provides anatomic information relating to arterial stenosis and is also capable of providing quantitative information about blood flow velocity. The system has been successful in the noninvasive diagnosis of extracranial cerebrovascular disease[19] and in the localization of peripheral arterial stenosis.[20] In the present study duplex scanning was used for the evaluation of diameter, velocity, and volume flow of the normal human superior mesenteric artery at rest and after a standardized test meal. The values obtained were compared with those measured at the common carotid artery, which is known for its stable flow conditions.

MATERIAL AND METHODS

A total of 20 healthy subjects, 14 women and six men, were investigated. The mean age was 30.1 years (range, 21 to 40 years). All subjects had a normal weight (mean, 60.5 ± 8.9 kg) and body surface area (mean, 1.69 ± 0.15 m^2) at a mean height of 168.5 ± 7.6 cm. They had fasted for at least 10

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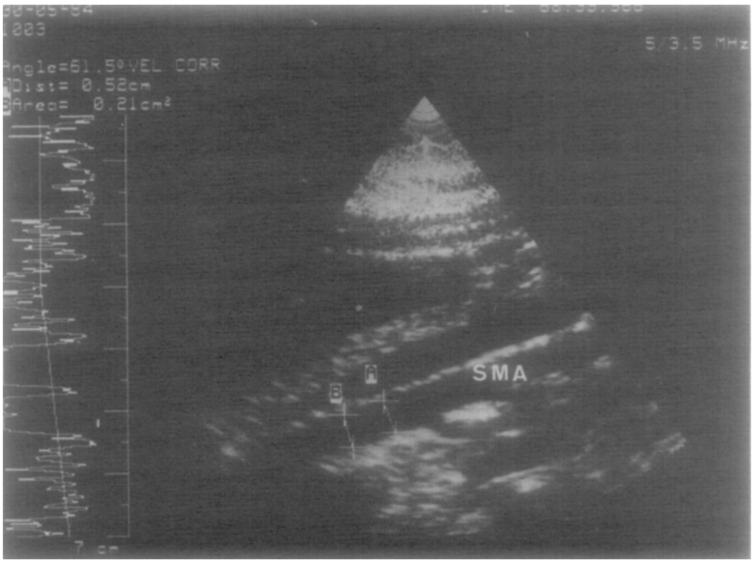

Fig. 1. B-mode image of the superior mesenteric artery of healthy volunteer. The image is used to measure diameter of artery. *Cursor* is placed at anterior and posterior wall of artery. Result is displayed in *upper left corner*.

hours (mean, 12.4 ± 2.6 hours). A standardized test meal consisting of 1000 kcal (4200 kilojoules) in 300 ml of chocolate pudding was given. The calories were divided between carbohydrates (50%, 125.5 gm), proteins (15%, 36.5 gm) and lipids (35%, 39.0 gm) reflecting the usual composition of a normal diet.

An ultrasonic duplex scanner (Ultra Imager, Honeywell Medical Electronics Div., Honeywell, Inc., Pleasantville, N.Y.) was used to evaluate the blood flow in the artery of interest. This device combines a B-mode imager and a pulsed Doppler unit with real-time spectral analysis. The oscillating 5 MHz transducer generates both the two-dimensional sector image and the Doppler data. The B-mode image allows the visualization of the artery. Thus the artery can be identified, anatomic variations are discernible, and the diameter of the artery can be measured. The B-mode image is also used to correctly place the sample volume of the pulsed Doppler beam into the artery and to ascertain the angle between the incident Doppler beam and the long axis of the vessel. The size of the sample volume needs to be adjustable to cover the diameter of the artery. The orientation of the Doppler beam, the Doppler angle, and the sample volume are electronically displayed on the screen. The Doppler signals are analyzed by a real-time spectrum analyzer that employs a digital fast Fourier transform (FFT) method. The analyzer provides 200 spectra per second with a resolution of 100 Hz. With the Doppler equation, the system computes the blood flow velocity (cm/sec). Velocity vs. time waveforms are obtained. The instantaneous velocity as well as the mean velocity can be determined with the implemented software.

After 15 minutes with the subject at rest in a recumbent position, the baseline measurements were performed. A sagittal scan in a left paramedian plane was used to identify the abdominal aorta. The superior mesenteric artery was found just ventral to the aorta behind the superior mesenteric vein. To avoid the turbulences of the bifurcation, recordings were taken from a straight segment 1 to 2 cm distal to the origin of the artery but proximal to the first side branches. First the diameter was measured (mean of two measurements) from the B-mode image (Fig. 1). The instantaneous velocity tracings were used to determine the peak systolic velocity, the velocity at the late systolic incision or reverse flow velocity, respectively, and finally the end-diastolic velocity (see *insert*, Fig. 2). The time-averaged mean velocity was computed from the mean of the outer and inner envelope of the Doppler spectra with the software of the duplex unit. A recording was taken 15 minutes after the test meal and repeated five times at 15-minute intervals. The brachial blood pressure was measured at rest and 45 minutes after food intake.

To test the stability of the carotid circulation, recordings from the midportion of the left common carotid artery were taken just after the measurement

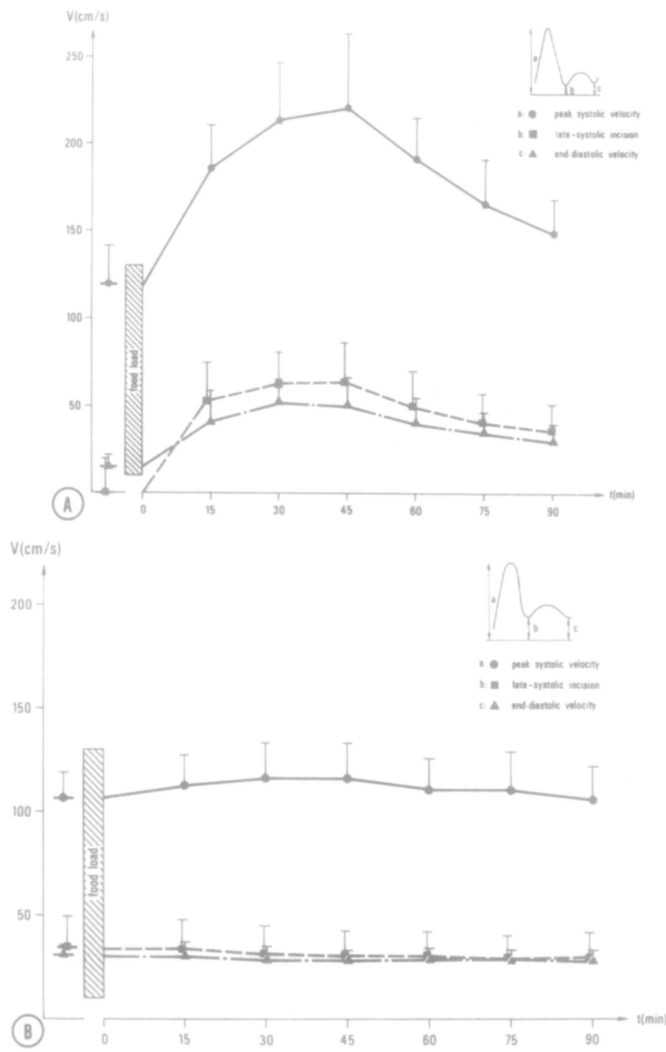

Fig. 2. A, Peak systolic, late systolic, and end-diastolic blood flow velocity in the superior mesenteric artery at rest and after standardized food load. **B,** Blood flow velocity patterns through the common carotid artery before and after test meal.

of the mesenteric blood flow at the same time intervals; the same parameters were used.

The statistical procedures include the paired Student *t* test and the Wilcoxon test from the Data Analysis Software (Mini-lab Inc., University Park, Pa.).

RESULTS

Vessel diameter. The mean diameter of the superior mesenteric artery was 0.60 ± 0.09 cm. At the left common carotid artery the mean diameter was almost identical (0.61 ± 0.05 cm) with no statistically significant ($p = 0.58$) difference. Although the diameter of the carotid artery remained unchanged after food intake, the diameter of the superior mesenteric artery became larger (Table I). The maximal increase in diameter was observed 45 minutes after the test meal, reaching 102% to 122% (mean, 112% ± 6.8%) of the initial values. As compared with the baseline measurement, the increase was statistically significant ($p < 0.0001$). With regard to the carotid artery the difference in diameter between the two arteries was significant ($p < 0.01$ to $p < 0.001$) between 30 and 75 minutes after food intake.

Waveforms. Typical waveforms characterizing the instantaneous flow pattern in the superior mesenteric artery are shown in Fig. 3. Early in systole, blood flow velocity increases rapidly. After having reached a peak, the velocity declines abruptly during the remainder of systole. Inflections in the descending slope were consistently observed. At the end of

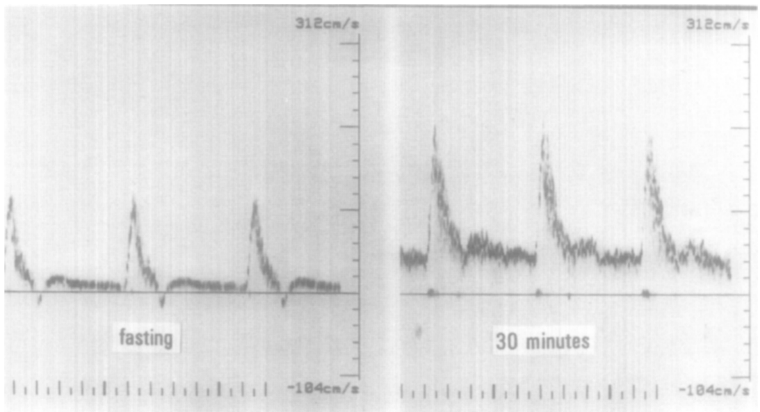

Fig. 3. Typical waveforms obtained from the superior mesenteric artery of healthy subject at rest and 30 minutes after test meal. Peak systolic, late systolic, and end-diastolic velocity significantly increase after food intake. Doppler frequency spectra are broadened.

Table I. Diameter, mean blood flow velocity, and volume flow of the superior mesenteric artery and common carotid artery at rest and at different times after test meal

	Superior mesenteric artery			*Common carotid artery*		
	Diameter (cm)	*Mean velocity (cm/sec)*	*Flow (ml/sec)*	*Diameter (cm)*	*Mean velocity (cm/sec)*	*Flow (ml/sec)*
Fasting	0.60 ± 0.09	22.2 ± 7.5	6.3 ± 2.6	0.61 ± 0.05	32.6 ± 5.9	9.6 ± 2.1
15 min	0.64 ± 0.09	51.0 ± 16.3	16.4 ± 6.3	0.61 ± 0.05	32.4 ± 6.0	9.5 ± 1.8
45 min	0.67 ± 0.09	57.0 ± 17.3	20.4 ± 7.4	0.60 ± 0.05	30.7 ± 5.4	8.8 ± 1.6
90 min	0.64 ± 0.07	35.1 ± 9.0	11.6 ± 3.6	0.61 ± 0.04	29.7 ± 4.7	8.7 ± 1.4

systole a marked incision or even a short reversal of flow was found. During early diastole, the flow accelerated again, then slowed progressively throughout the remainder of diastole. The typical waveform of the common carotid artery is quasi-steady with late systolic and diastolic flow remaining well above zero throughout the cardiac cycle. Healthy, young persons may occasionally demonstrate a short period of late systolic/early diastolic flow reversal.

Flow velocity. In healthy fasting subjects the mean of the peak systolic velocity in the superior mesenteric artery was 119.6 ± 22.8 cm/sec. The blood flow velocity dropped to −0.4 ± 20.1 cm/sec at the time of the late systolic incision and was 15.8 ± 7.8 cm/sec at the end of diastole. The changes in blood flow velocity induced by the test meal are demonstrated in Fig. 2, *A*. Immediately after food intake blood flow velocities of the superior mesenteric artery increased significantly ($p < 0.0001$) at the three defined sites of the heart cycle. The highest values were reached after 45 minutes. Afterwards, blood flow slowly decelerated and almost reached the baseline values 90 minutes after the test meal. At 45 minutes the systolic velocity had nearly doubled the baseline value (189.1% ± 50.7%) and the diastolic velocity was almost three times (350% ± 175%) higher than before the test meal. The most prominent finding was the loss of the late systolic incision with an increase in velocity from −0.4 ± 20.1 cm/sec to 63.5 ± 23.5 cm/sec.

In the common carotid artery the peak systolic velocity at rest was 107.8 ± 12.7 cm/sec, the velocity at the late systolic incision 34.7 ± 15.0 cm/sec, and the end-diastolic velocity 31.0 ± 5.8 cm/sec. After the test meal only minimal changes of the velocity parameters were detectable (Fig. 2, *B*).

Mean flow velocity. The time-averaged mean flow velocity (Table I) of the mesenteric artery at rest was 22.2 ± 7.5 cm/sec. This value was significantly ($p < 0.0001$) lower than the mean velocity of the common carotid artery (32.6 ± 6.0 cm/sec). Although the mean carotid velocity was not affected by the food load, the mean mesenteric velocity increased significantly ($p < 0.0001$). Forty-five minutes after the meal the mean mesenteric flow velocity was 1.8 times higher than the fasting value. The increase in diastolic forward flow is mainly responsible for the increase in mean mesenteric velocity during

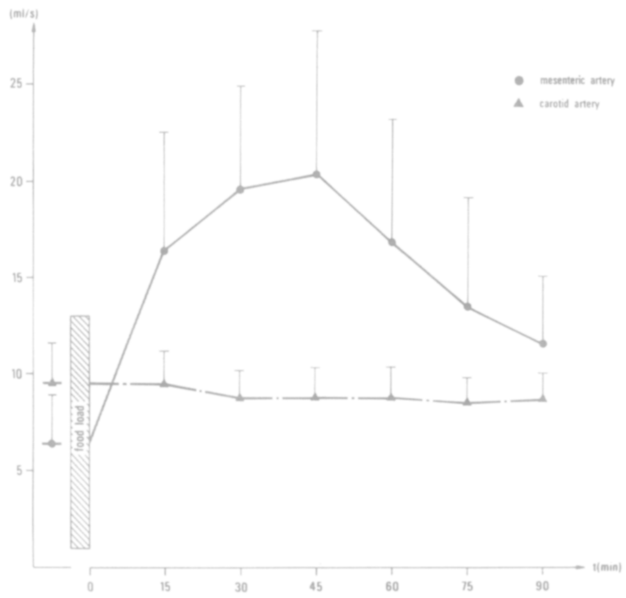

Fig. 4. Volume flow through normal superior mesenteric and common carotid artery before and after food intake. A steep postprandial increase in mesenteric blood flow with maximal hyperemia after 45 minutes can be observed.

digestion. A high correlation coefficient (0.88) was found between the mean mesenteric velocity and the diastolic flow velocity. The correlation of the velocity at the late systolic incision (0.63) and the systolic velocity (0.60) was less obvious.

Volume flow. In healthy fasting subjects the computed blood flow through the superior mesenteric artery was 6.3 ± 2.6 ml/sec. No significant correlation was found between blood flow and the instantaneous velocity parameters or the individual subject characteristics, such as the body surface area. At rest, blood flow through the carotid artery (9.5 ± 2.1 ml/sec) was significantly ($p = 0.0003$) higher than through the mesenteric artery. During digestion a slight tendency toward reduced flow volumes was observed in the common carotid artery. The difference, however, was statistically insignificant. On the other hand, a marked ($p < 0.0001$) postprandial hyperemia of the superior mesenteric artery was recorded (Table I, Fig. 4). Almost immediately after the end of the test meal a steep increase in mesenteric blood flow was observed. Fifteen minutes after ingestion of the food load, flow through the mesenteric artery was 1.8 times higher than at rest. At the time of maximal hyperemia (45 minutes) mesenteric flow was 2.5 times higher than in the fasting state (range, 0.8-5.1). After 45 minutes blood flow decreased slowly. At the end of the observation period (90 minutes), however, blood flow was still significantly higher than before the test meal. The ratio of mean blood flow in the carotid artery to mean blood flow in the superior mesenteric artery dropped from 1.75 at rest to 0.47 at 30 minutes after the test meal (Fig. 5).

The resistance index, which is the systolic velocity minus the velocity at the time of the incision divided by the systolic velocity (see *insert,* Fig. 6) was 1.0 for the mesenteric artery and 0.73 for the carotid artery in the fasting subject. The difference between the two vessels was significant ($p < 0.0001$). Within the first 15 minutes after the meal the resistance index of the mesenteric artery dropped to 0.72 and approximated the values obtained for the carotid artery. During the observed period of digestion the resistance of the mesenteric artery was not significantly different from the resistance of the carotid artery. The resistance of the carotid artery was augmented between 30 minutes ($p = 0.013$) and 90 minutes ($p = 0.005$) postprandially.

At rest the ratio between the diastolic and the systolic velocity was 0.13 at the mesenteric artery and 0.29 at the carotid artery ($p < 0.0001$). During digestion the diastolic/systolic velocity ratio changed in both arteries. At the time of maximal postprandial hyperemia, significantly ($p < 0.0001$) higher ratios in the mesenteric artery and significantly ($p = 0.001$) lower ratios in the carotid artery were observed. The ratio between the two arteries 30 to 45 minutes after food intake was no longer significantly different.

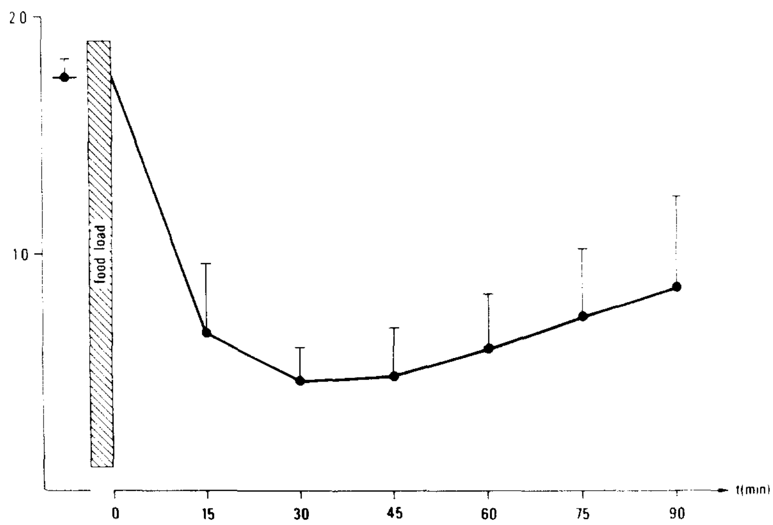

Fig. 5. Ratio of mean blood flow of carotid artery to mean blood flow of mesenteric artery dropped from 1.75 (fasting) to 0.47 (30 minutes after test meal).

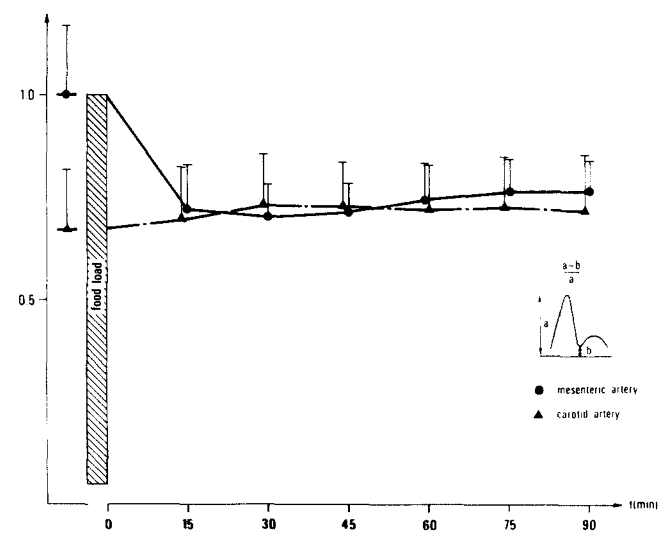

Fig. 6. Resistance index of the superior mesenteric artery is significantly higher than in the common carotid artery in the fasting subject. During postprandial hyperemia of the gut resistance index of both arteries is not significantly different.

During digestion the heart rate slowly increased from a baseline value of 63 ± 12 beats/min to 68 ± 11 beats/min after 45 minutes ($p = 0.024$). The brachial pressure was not affected by the food load (116 ± 9 mm Hg/71 ± 6 mm Hg at rest vs. 116 ± 12 mm Hg/69 ± 6 mm Hg after 45 minutes).

DISCUSSION

With the use of a duplex system, which combines a B-mode imager and a Doppler unit, it is now possible to assess noninvasively the blood flow dynamics in the human mesenteric artery. In contrast to the previous techniques the artery does not need to be surgically exposed, no catheterization is needed, and no tracer substance is injected. Ultrasound waves transmitted through the intact skin are supposed to be harmless. The test causes no pain and almost no discomfort to the patient and can be repeated if necessary. The hitherto existing methods of splanchnic blood flow measurement were rather demanding procedures in terms of laboratory facilities and expertise. Selective assessment of flow through one of the three major splanchnic arteries was even a greater challenge. Thus, it is not surprising that only scattered reports on human mesenteric blood flow are available.[15,16] Our knowledge of mesenteric blood flow derives mainly from estimated allotments of a calculated total splanchnic flow.*

The report also shows that this technique allows the assessment of the hemodynamic parameters at rest and after a test meal and thereby offers a circulatory stress test of the gut. By analogy with better known circulatory systems such as the skeletal muscle or the heart, it is assumed that mesenteric blood flow increases after food ingestion in response to the increased metabolic requirements associated with digestion. Our findings indicate a steep increase in blood flow across the main stem of the superior mesenteric artery within 15 minutes after the test meal. This increase was found to be maximal 45 minutes after food intake and to decline slowly thereafter. At the time of maximal postprandial hyperemia, blood flow through the superior mesenteric artery was on the average 2.5 times higher than in the resting state. At the same time the instantaneous blood flow velocity increased. Besides the marked acceleration of blood flow during systole, the late systolic and the diastolic forward flow were augmented. The latter had a stronger influence on the mean velocity than the short systolic peak. The hyperemic response is comparable to the well-documented hyperemia of the femoral artery induced by exercise or arterial occlusion by a pressure cuff applied to the extremity.[24,25]

In addition to the increased flow velocity the cross-sectional area of the vessel also got larger. According to Poiseuille's law, blood flow varies directly with the fourth power of the radius of the artery. Thus the diameter measurement is the critical factor in determining the volume flow. In our computation of blood flow an overestimation of the diameter by 1 mm would result in an overestimation of the blood flow through a 7 mm diameter artery by 30%. Repeated measurements demonstrate that the error in the blood flow calculations caused by an under- or overestimation of the diameter does not exceed $\pm 10\%$. For electromagnetic flow measurements an accuracy of 5% to 10% error was reported.[2] Considering the biologic variability and the large and highly significant increase in mesenteric flow after a meal, this error of the method is acceptable.

Accurate measurements of blood flow velocity are possible provided that the angle of the incident Doppler beam with respect to the vessel axis is known. For example, if the Doppler angle diverges from a presumed angle of 60 degrees by 2 degrees, an error of 7% is induced. The combination of the B-mode scan with the Doppler unit allows correct determination of the Doppler angle, resulting in accurate velocity measurements.

Calculation of velocity ratios eliminates eventual errors in the velocity measurements.[26] Moreover, the indices provide information about the resistance of the vascular bed. The resistance index of the mesenteric artery decreased immediately after the test meal and approximated the resistance index of the carotid artery. The resistance across the carotid system increased slightly during digestion. Blood flow through the carotid artery, however, did not significantly decrease during digestion. The higher resistance index may be caused by the external carotid artery. Thus, cerebral circulation seems not to contribute significantly to the redistribution of blood flow during digestion.*

The cardiac function proved to be minimally affected by the intestinal hyperemia. The heart rate slightly increased, whereas the brachial blood pressure remained unchanged.

The high response of the mesenteric artery to the food load may be attributable to the ample test meal. A maximal stimulation of the mesenteric blood flow was intended. Not yet known is the influence of different amounts of calories. The consistency and the nutritive quality of the meal including the percentage of carbohydrates, proteins, and lipids could also determine the reactive hyperemia. These factors may not only influence the maximal response of the mesenteric circulation but also the time of maximal hyperemia as well as the duration of the hyperemia.

Using a dye solution technique, Buchardt Hansen et al.[17] studied splanchnic blood flow in patients with abdominal angina before and after arterial reconstruction. Fasting splanchnic blood flow was found to be the same in both normal subjects and those with intestinal angina. After a test meal was eaten, blood flow did not increase in patients with intestinal angina. Patients who underwent surgical correction had an appropriate increase in splanchnic blood flow associated with eating. Preliminary results from our laboratory confirm these findings. The described stress test of the gut is probably the most specific and sensitive means to diagnose intestinal ischemia.

Besides vascular occlusive disease,[17,27,28] visceral circulation is disturbed in a variety of gastrointestinal

*References 13, 14, 17, 21-23.

*References 3, 6, 7, 10, 11.

diseases.[7] Assessment of the hemodynamic parameters may be of diagnostic value and might shed light on the underlying pathophysiologic conditions.

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