Gastrointestinal Blood Flow in the Dog

By John P. Deloney, M.D., Ph.D., and James Custer, B.S.

Measurement of blood flow to the individual gastrointestinal organs has been hampered by limitations of methodology. The oldest and most direct experimental technique for estimating blood flow to an organ is timed collection of its total venous outflow. Traumatic surgical procedures are required to accomplish such collections from the stomach, intestine, or colon. This method is not applicable to the pancreas, gall bladder, duodenum or esophagus because these latter organs are drained by multiple small vessels. Placement of flowmetering devices on or in the major vessels also requires relatively extensive operative manipulation. The complexity of the arterial inflow and venous outflow pathways of the gastrointestinal organs makes estimates for an individual organ by means of a flowmeter somewhat questionable. Furthermore, the flowmeter devices, whether based on thermal or electromagnetic principles, are generally more useful for estimating relative changes in blood flow than for determining absolute quantities.

In recent years indicator clearance techniques have been developed which allow measurement of tissue blood flow with relatively little disturbance of normal function. The particular method used in the present study was the radiotrubdium distribution technique. The first part of the investigation was an inquiry into the suitability of this method for measurement of blood flow to the various gastrointestinal organs. The method gave accurate estimates of total blood flow to the stomach, small intestine and colon. Indirect evidence suggested that it was probably suitable for pancreas, gall bladder and esophagus. In the second part of the study the method was employed for the measurement of blood flow to the gastrointestinal organs of the intact anesthetized dog.

I. Validation Experiments

The radiotrubdium clearance technique is based on the assumption that the initial distribution of the isotope among all the organs is identical to that of the cardiac output; i.e., the fraction of the total injected isotope contained in an organ for a short time after injection is equal to the fraction of the cardiac output perfusing that organ. Clearly this assumption would be correct if every organ of the body extracted and held 100% of the isotope reaching it via the arterial blood. That such is not the case in the dog is evident from the finding that appreciable quantities of the isotope remain in the blood, therefore not in the tissues, during the time interval 30 to 60 seconds after injection. Previous experiments have indicated that 30 seconds after injection as much as 20 to 30% of the isotope is still in the blood, therefore mostly in large vessels. Despite this initial overall body extraction of approximately 70 to 80%, it is still quite possible that any particular organ might contain an amount of radiotrubdium equal to what it would have held, had each organ extracted 100% during the first capillary passage. To evaluate the accuracy of the method for any particular organ one need only examine the time course of its arterial and venous Rb activity during the first minute following injection of a slug of the isotope. The validation of the radiotrubdium distribution method for measuring blood flow to the stomach has been the subject of a previous report. Radiotrubdium and radiotrubdium have been shown to distribute similarly.

Methods

Mongrel dogs, fasted for approximately 18 hours, were anesthetized with sodium pento-
barbital (30 mg/kg body weight) and a midline abdominal incision was made. Polyethylene catheters of identical caliber and length were placed in the appropriate veins (portal, inferior mesenteric, gastrosplenic) with a second one in the aorta via the femoral artery, the tip lying approximately at the level of the celiac artery. A third larger catheter, with a capacity of 3 cc, was passed via the femoral vein until its tip lay in the thoracic inferior vena cava. A bolus of 1 cc of Rb$^{86}$Cl was injected into the catheter. At the chosen time the radioisotope was flushed rapidly into the circulation with 10 cc of 0.9% sodium chloride solution. At the same time blood was withdrawn at a constant rate of 38.2 cc/min by a motor driven syringe from the appropriate mesenteric vein and from the aorta. The blood was drawn through spirals of tubing fixed in front of beta scintillation crystals whose outputs were fed into recording rate meters. The voltages of the two rate meters were adjusted so that an equal concentration of the isotope in the spiral counting chambers would give identical counting rates in the two systems. In this fashion the time courses of the concentrations of the isotope in the arterial blood and in the venous blood of the gastrointestinal organ were monitored and compared.

Results

Figures 1 and 2 illustrate typical simultaneous arterial and venous dilution curves for the portal vein, and for the inferior mesenteric vein. Figure 3 shows the concentration course in the gastrosplenic vein which, with the spleen removed, represented gastric venous blood. It can be seen in each figure that the arterial and venous Rb$^{86}$ concentrations were essentially identical during the period from 30 to 60 seconds after systemic injection of the isotope. One consequence of this finding is that the isotope content of the organs being drained by these veins does not change during the time interval in question. The same quantity of Rb$^{86}$ is entering in the ar-

**FIGURE 1**

Simultaneous arterial and portal vein isotope concentrations. Read from right to left.
arterial blood as is leaving in the venous blood, assuming arterial and venous flows to be equal. Since the organ isotope content does remain constant during this time the precise moment of stopping the circulation is not crucial. Reading from right to left, each figure shows also a semilogarithmic extrapolation of the arterial down slope. The isotope content of the organ at any moment is described by the arterial inflow rate multiplied by arterial isotope concentration, as represented by the arterial dilution curve, minus venous outflow multiplied by venous concentration, as represented by the area of the venous dilution curve.

Consider a theoretically ideal tracer substance which would be extracted completely from the blood by every organ of the body during its first passage through the capillaries, and whose distribution would therefore be identical with that of the cardiac output. In such a situation the arterial concentration curve would fall semilogarithmically to zero, that is, no arterial recirculation would occur. Since all the isotope would be extracted from the blood, venous concentration would be zero. The isotope content of each organ in this situation would be represented by the area of the arterial dilution curve times the blood flow to the organ. To determine if the isotope content of an organ does in fact represent 100% of its share of the cardiac output one need only compare the actual content as determined by the difference between the arterial and the venous curves and the theoretical 100% as described by the area under the extrapolated arterial curve. The areas for each are indicated in table 1. It is apparent from these estimates that each of the organs examined did in fact contain an amount of isotope approximately equivalent to 100% of its share of the cardiac output. Thus Rb$^{86}$ behaves as though it were a nearly ideal tracer substance for measuring blood flow to these particular organs. For this situation to prevail an organ cannot extract all of the Rb$^{86}$ entering it. If it did so it would contain an excess of isotope at 30 seconds.
FIGURE 3

Simultaneous arterial and gastrosplenic vein isotope concentrations. With the spleen removed, gastrosplenic venous blood represents primarily gastric effluent.

having picked up recirculating Rb\textsuperscript{8} in addition to 100\% of the first slug reaching it. However, the organ might retain 80 to 90\% of the first slug and then the equivalent of the remaining 10 to 20\% from the recirculating isotope. Examination of the curves indicates that this describes the observed events for the stomach, intestine and colon. Unfortunately, similar data on venous concentration of radiorubidium are impossible to obtain for the gall bladder and esophagus. Pure pancreatic venous blood can be withdrawn but not in quantities sufficient to make accurate and continuous estimates of venous concentration over the time interval in question.

It can be concluded that the stomach, small intestine, and colon do contain a fraction of the total injected Rb\textsuperscript{8} equivalent to their respective shares of the cardiac output during the period from 30 to 60 seconds after injection. Multiplication of the cardiac output by this fraction gives a good measure of the actual isotope concentration in the respective areas under time.

**TABLE 1**

Comparison of Actual Areas Under Arterial and Venous Curves with Areas Under Semilogarithmically Extrapolated Arterial Curves from the Time of Isotope Injection to the Time of Sacrifice (30 seconds). From records shown in figures 1, 2, and 3

<table>
<thead>
<tr>
<th>Vein</th>
<th>Arterial curve</th>
<th>Venous curve</th>
<th>Difference</th>
<th>Extrapolated arterial curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gastrosplenic (stomach)</td>
<td>54.5 cm\textsuperscript{2}</td>
<td>8.1 cm\textsuperscript{2}</td>
<td>46.4 cm\textsuperscript{2}</td>
<td>49.4 cm\textsuperscript{2}</td>
</tr>
<tr>
<td>Inferior mesenteric (colon)</td>
<td>17.7 cm\textsuperscript{2}</td>
<td>4.7 cm\textsuperscript{2}</td>
<td>13.0 cm\textsuperscript{2}</td>
<td>13.3 cm\textsuperscript{2}</td>
</tr>
<tr>
<td>Portal (all gastrointestinal organs)</td>
<td>32.7 cm\textsuperscript{2}</td>
<td>7.6 cm\textsuperscript{2}</td>
<td>25.1 cm\textsuperscript{2}</td>
<td>22.5 cm\textsuperscript{2}</td>
</tr>
</tbody>
</table>
of blood flow to these organs. It seems likely that the same situation may prevail for the anatomically similar esophagus. By analogy, the method probably gives good estimates for gall bladder and pancreas, but no evidence is available from these studies to support this contention. Sapirstein found a constancy of pancreatic isotope content in rats killed at varying time intervals after the injection of K$^{42}$ or Rb$^{86}$. This is equivalent to the observation that the arterial and venous isotope concentrations remain equal to one another from approximately 25 seconds to at least 60 seconds after injection of the isotope, and therefore lends support to the validity of the method for measuring pancreatic blood flow.

II. Measurements of Blood Flow to the Gastrointestinal Organs of the Intact Dog

**Methods**

All experiments were done on mongrel dogs fasted for 18 hours. The dogs were anesthetized with sodium pentobarbital (30 mg/kg body weight). Catheters were placed in the thoracic inferior vena cava and in the abdominal aorta via the femoral vessels. A precise volume of the isotope (approximately 1 cc) was injected by means of a Krogh-Keys syringe pipet into the vena caval catheter, and at the appropriate time was washed rapidly out of the catheter into the circulation with approximately 10 cc of 0.9% sodium chloride solution. At the same time, a motor driven constant rate syringe was started, withdrawing arterial blood from the aorta through the radioactivity monitoring apparatus described in the preceding section. Thirty seconds after injection of the isotope the animal was sacrificed by injecting 100 cc of saturated potassium chloride through the same vena caval catheter, inducing cardiac standstill within 5 to 7 seconds. The abdomen was then opened, the organs removed, and all extraneous fat, vascular and connective tissues trimmed from their surfaces. Each organ was blotted free of gross moisture, weighed, and digested in concentrated hydrochloric acid. A 2 cc aliquot was weighed and counted for five minutes in a gamma scintillation detector along with duplicate 2 cc aliquots of the diluted isotope "standard." To make up the "standard" isotope solution the same syringe pipet was used to put exactly the same amount of isotope that had been injected into the dog, into a 500 cc volumetric flask. To determine the amount of isotope injected into the dog as measured by the beta-crystal ratemeter system the spiral cuvette was filled with the diluted standard isotope solution and its level of activity recorded. Cardiac outputs were calculated, using the area under the extrapolated arterial isotope dilution curve and the conventional Hamilton equation. Blood flow to each organ was calculated by multiplying the cardiac output times the fraction of the total injected radioisotope found in that organ. Blood flow per gram of tissue was determined simply by dividing the total blood flow per minute by the weight of the organ. These calculations have been described in detail in a previous publication.

**Results**

Table 2 gives a summary of the results. Average body weight was 15.4 kg and average cardiac output was 176 cc/kg body weight/min. This is essentially identical to the average cardiac output obtained in a previous but separate series of experiments and is also in good accord with other studies using Cardio-Green dye. Average stomach weight was 6.6 g/kg body weight or 0.66% of the body weight. This is also essentially identical with previously reported values. The whole stomach received 1.90% of the cardiac output or 0.51 cc/min-g, again approximately equal to results obtained in the previous experiments using radiopotassium. The body of the stomach received a mean of 0.56 cc/min-g while the mean for the antrum was 0.41 cc/min-g. In 7 of the 11 experiments the perfusion rate of the gastric body exceeded that of the antrum. The difference of the means was not statistically significant.

The blood flow to only the distal 4 to 6 cm of esophagus was evaluated in this study and averaged 0.21 cc/min-g. The duodenum was treated separately and was considered, for this experiment, to be the first 12 to 15 cm of intestine distal to the pylorus. In the initial experiments the duodenum was divided into the portion lying between the pyloric ring and the ampulla of Vater and an equal length distal to the ampulla. The perfusion rate was invariably identical in these two segments; in later experiments and for the final mean, the duodenum was treated as a single segment of intestine. Duodenal blood flow was found to be 0.70 cc/min-g of tissue.
The rest of the small intestine received a mean of 6.48% of the cardiac output which represented 0.72 cc/min-g of tissue. With secretions wiped from the mucosa and the mesentery and vascular tissue carefully trimmed from the serosal surface the weight of the intestinal wall itself averaged 1.64% of the body weight.

The colon treated in the same fashion averaged 0.34% of the body weight. It received 1.61% of the cardiac output or 0.82 cc/min-g of tissue.

The pancreas received 0.69% of the cardiac output of 0.60 cc/min-g of tissue. Again this value is very close to that in a previously reported series of experiments done with radiopotassium, where the mean blood flow was 0.63 cc/min-g. The pancreas represents a relatively constant portion of the body weight of the dog, 0.19%. There is, incidentally, much less variability in this value than in those obtained for the other gastrointestinal organs. The gall bladder perfusion rate averaged 0.39 cc/min-g of tissue.

Discussion

In a previous study relating only to gastric blood flow, one group of experiments was done on unanesthetized dogs and a second series on dogs under pentobarbital anesthesia. Blood flow to the stomach was essentially identical in the two groups. Thus, for the stomach, the values obtained in the present series of experiments with pentobarbital anesthesia should represent an accurate estimate of average gastric blood flow under normal fasting circumstances. Although similar experiments have not been done in unanesthetized animals for the other gastrointestinal organs, there is no reason to believe that they differ from the stomach with regard to the influence of pentobarbital on perfusion rate. That the values obtained for stomach and pancreas in this series of experiments is so nearly identical to those measured with a different isotope in separate studies, lends considerable support to the validity of the results.

Table 3 summarizes results in terms of an "average" 15 kg dog. The sum of the mean values for fractions of the cardiac output perfusing stomach, small intestine, colon, and pancreas is 10.7%. Total portal vein flow would also include blood draining from the spleen, mesentery and omentum. Mean cardiac output for a 15 kg dog would be approximately 2600 cc/min; 10.7% of this output would be approximately 20 cc/kg body weight/min. Addition of the blood flow from the mesentery, spleen and omentum brings this figure into the 25 to 30 cc/min-kg range. This agrees well with the results of studies carried out by other methods. In his extensive review of the mesenteric circulation, Crim concluded "that the portal venous blood flow in dogs of 10 to 20 kg body weight having a 'normal' arterial pressure of 130 mm is about 25 ml/min-kg."

Virtually no quantitative information is available on blood flow to the esophagus. One exception is the work of Steiner and Mueller who, using the K distribution method in the rat, obtained a value of 0.6 cc/min-g of tissue. Only the distal esophagus was studied in the present experiments and the mean blood flow was found to be 0.21 cc/min-g, a considerably smaller perfusion rate than that of the other gastrointestinal organs. The rat and the dog apparently show a marked species difference in this respect.

Similarly, no information appears to be available regarding blood flow to the gall bladder. The mean value obtained here was 0.39 cc/min-g. The values ranged from 0.15 cc/min-g to 0.91 cc. The reason for this wide scatter of data is not apparent. One might speculate that a significant portion of the gall bladder blood flow passes through its attachments to liver and that anatomic variations in this area could be an explanation. A second factor could be varying degrees of distention with bile at the time blood flow was measured.

Sapirstein's report indicated that a mean of 2.5% of the cardiac output perfused the dog stomach and that this represented 0.4 cc/min-g of tissue. The mean cardiac output of his dogs was 189 cc/kg-min, essentially the same as that of the present study. One can only conclude that the stomachs of his ani-
Cardiac Output, Gastrointestinal Organ Weight and Perfusion of Intact Dogs

**TABLE 2**

<table>
<thead>
<tr>
<th>Experiments number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dog wt, kg</td>
<td>9.5</td>
<td>9.5</td>
<td>9.1</td>
<td>19.1</td>
<td>21.4</td>
</tr>
<tr>
<td>Cardiac output, cc/min·kg</td>
<td>158</td>
<td>253</td>
<td>255</td>
<td>184</td>
<td>285</td>
</tr>
</tbody>
</table>

**Stomach**
- Per cent of body weight, %: .66, .78, .68, .61, .73
- Per cent of cardiac output, %: 3.19, 2.62, 2.99, 1.82, 1.20
- Whole stomach perfusion, cc/min·g: .58, .85, 1.13, .56, .45
- Antral perfusion, cc/min·g: .45, .81, .78, .13, .57
- Corpus perfusion, cc/min·g: .75, .99, 1.27, .69, .48

**Small intestine**
- Per cent of body weight, %: 1.39, 1.95, 1.54, 1.64, 1.64
- Per cent of cardiac output, %: 7.41, 9.12, 9.44, 7.78, 4.59
- Perfusion, cc/min·g: .84, 1.18, 1.50, .88, .79

**Colon**
- Per cent of body weight, %: .46, .33, .33, .34, .35
- Per cent of cardiac output, %: 1.78, 1.41, 2.11, 2.28, 1.06
- Perfusion, cc/min·g: .61, 1.08, 1.61, 1.25, .76

**Pancreas**
- Per cent of body weight, %: .23, .22, .22, .20, .16
- Per cent of cardiac output, %: 1.05, .58, .71, 1.10, .39
- Perfusion, cc/min·g: .72, .68, .81, 1.02, .59

**Esophagus**
- Perfusion, cc/min·g: .21, .28, .51, .27, .18

**Duodenum**
- Perfusion, cc/min·g: .76, .87, 1.07, .69, .94

**Gallbladder**
- Perfusion, cc/min·g: .51, .36, .24

The weights of the gastrointestinal organs were relatively larger than those of the present series or that poorly perfused surface fat and connective tissue were included in the estimates.

Having found entirely comparable values in three separate groups of animals, using two different isotopes, it seems fair to conclude that mean total gastric blood flow in the fasting dog is approximately 0.50 to 0.55 cc/min·g of tissue.

Because the duodenum is an area of special interest both to clinicians and physiologists, it was studied separately from the rest of the intestine. As noted above, the first and second portions of the duodenum had identical blood flows. Although physiologic gradients of activity are undoubtedly present in the small intestine, no difference was noted here in blood flow to the duodenum, compared to the remainder of the small intestines.

**TABLE 3**

<table>
<thead>
<tr>
<th>Weight</th>
<th>Fraction of cardiac output</th>
<th>Blood flow</th>
<th>Perfusion rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>%</td>
<td>cc</td>
<td>cc/min·g</td>
</tr>
<tr>
<td>Stomach</td>
<td>100</td>
<td>1.9</td>
<td>50</td>
</tr>
<tr>
<td>Intestine</td>
<td>270</td>
<td>6.5</td>
<td>180</td>
</tr>
<tr>
<td>Colon</td>
<td>50</td>
<td>1.6</td>
<td>40</td>
</tr>
<tr>
<td>Pancreas</td>
<td>30</td>
<td>0.7</td>
<td>18</td>
</tr>
<tr>
<td>Gall bladder</td>
<td>2</td>
<td>0.04</td>
<td>1</td>
</tr>
</tbody>
</table>

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Mean ± Standard error

18.2 23.2 25.0 9.1 12.7 12.7 15.4 kg
108 156 149 133 132 121 176 cc/min-kg

.69 .63 .66 .58 .59 .65 .66% .26
1.14 1.94 1.46 1.00 2.70 1.14 1.90% .08
.18 .49 .35 .22 .60 .23 .51 cc/min-g .08
1.13 .24 .18 .19 .72 .26 .41 cc/min-g .08
.17 .52 .39 .24 .57 .20 .56 cc/min-g .10
1.58 1.19 1.97 2.11 1.27 1.69 1.04% .61
8.66 3.86 3.86 6.49 5.95 4.24 6.48% .11
.59 .50 .29 .41 .62 .30 .72 cc/min-g .48
.28 .33 .43 .42 .28 .19 .34% .08
1.45 1.43 1.86 1.58 1.96 .73 1.01% .09
.56 .86 .65 .50 .89 .46 .82 cc/min-g .10
.19 .15 .20 .15 .19 .21 .19% .03
.84 .60 1.02 .38 .45 .45 .69% .09
.50 .62 .76 .33 .32 .26 .60 cc/min-g .09
.17 .14 .12 .12 .20 .16 .31 cc/min-g .09
.69 .59 .42 .45 .74 .49 .70 cc/min-g .07
.24 .15 .38 .27 .01 .46 .39 cc/min-g .07

GASTROINTESTINAL BLOOD FLOW

With few exceptions, studies on the intestinal blood flow have not treated the colon separately. The finding that mean colonic blood flow in the dog exceeded that of the small intestine was unexpected. Gerber, using an electromagnetic flowmeter, found colonic blood flow was 0.73 cc/min-g. While this estimate agrees reasonably well with that of the present study, it should be pointed out that his values for duodenum, jejunum and ileum were all considerably higher than those reported here.

Anatomic complexities make direct estimates of pancreatic blood flow of little value. Because the pancreas shares a common blood supply with the duodenum, the two must be separated to measure pancreatic blood flow. Such a traumatic procedure undoubtedly influences the blood flow rate. Sapirstein, using radiopotassium in the dog, found a mean pancreatic perfusion of 1.0 cc/min-g or 1.6% of the cardiac output. Steiner and Mueller, using Rb in the rat, obtained a value just half as large, 0.5 cc/min-g. The mean value for pancreatic perfusion in the present study was 0.60 cc/min-g, which is in excellent accord with our previous experiments employing radiopotassium in the dog.4

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While the radioisotope distribution method gives reproducible and accurate measures of blood flow to the gastrointestinal organs it has some disadvantages. First, blood flow is measured over a very brief span of time, the few seconds during which the bolus of isotope is passing the origins of the celiac and mesenteric arteries in the aorta. Because the animal must be sacrificed to analyze isotope content of the tissues, only a single measurement can be made for each and therefore fairly large groups of animals must be used. The effects of drugs or physical agents or operations can be assessed only by comparing such groups. Using each animal as its own control, as is done in acute experiments with flowmetering devices, has advantages in this regard. On the other hand, the radioisotope distribution method involves little or no disturbance of the animal's normal physiology and can provide information on blood flow to organs inaccessible to study by any other means. Furthermore, data can be obtained regarding chronic alterations in gastrointestinal blood flow induced by operative procedures or chronic administration of drugs.

Summary
That the radiorubidium distribution method provides good estimates of blood flow to the gastrointestinal organs was demonstrated by comparing the arterial concentration course of the isotope with the simultaneous venous concentration for the individual organs. Blood flow to stomach, intestine and colon are accurately assessed by this method. Estimates for pancreas, gall bladder, esophagus and duodenum are probably correct. Average perfusion rates in the pentobarbital anesthetized dog are, in cc/min·g of tissue:—esophagus, 0.21; stomach, 0.51; duodenum, 0.70; small intestine, 0.72; colon, 0.82; pancreas, 0.60; and gall bladder, 0.39.

References
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