Systemic and Regional Hemodynamic Changes during Food Intake and Digestion in Nonanesthetized Dogs

By K. Fronek, M.D., C.Sc., and L. H. Stehlgren, M.D.

ABSTRACT
In nine dogs under pentobarbital anesthesia, electromagnetic flow transducers were implanted around the ascending aorta, brachiocephalic artery, superior mesenteric artery, and iliac artery. A catheter to measure arterial pressure was implanted into the thoracic aorta. After full recovery, hemodynamic variables were measured daily in conscious dogs in five sets of recordings: control, during anticipation of food, during actual food intake, and 1 hour and 3 hours after completion of ingestion. During food intake there was a generalized sympathomimetic stimulation characterized by a significant increase in cardiac output with a peak of 142%, heart rate (176%), arterial blood pressure (147%), while the ratio of flow in the superior mesenteric artery to cardiac output decreased from 8.9% to 7.6% (P<0.05). Flow in the brachiocephalic artery increased during food intake to 196% and that in the iliac artery dropped to 75.4%. The possibility was discussed that a certain level of sympathomimetic stimulation may signal the diminishing or ending of ingestion. During digestion (at 1 and 3 hours after ingestion), there were no significant changes in cardiac output, heart rate, and mean arterial blood pressure, whereas the flow in the superior mesenteric artery increased to 133% and mesenteric regional resistance decreased to 82%, and flows in the brachiocephalic and iliac arteries decreased to 86.5% and 74.6%, respectively. The ratio of flow in the superior mesenteric artery to cardiac output increased to 8.9% and 12.5% in the third hour. These results indicate that a redistribution of blood flow occurs during digestion with a preference for the vascular bed of the superior mesenteric artery.

ADDITIONAL KEY WORDS: superior mesenteric artery flow, heart rate, brachiocephalic artery flow, iliac artery flow, cardiac output, arterial blood pressure, distribution of blood flow, total peripheral resistance, regional resistance.
Hemodynamic Changes during Anticipation of Food, Ingestion, and Digestion

TABLE 1

<table>
<thead>
<tr>
<th></th>
<th>No. dogs</th>
<th>Control</th>
<th>Anticipation period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean arterial blood pressure (mm Hg)</td>
<td>9</td>
<td>95.8 ± 3.3</td>
<td>124.7*</td>
</tr>
<tr>
<td>Heart rate (beats/min)</td>
<td>9</td>
<td>88.0 ± 6.7</td>
<td>140.0 ± 6.9</td>
</tr>
<tr>
<td>Cardiac output/kg (ml/min/kg)</td>
<td>9</td>
<td>137.3 ± 5.8</td>
<td>157.5 ± 4.7</td>
</tr>
<tr>
<td>Brachiocephalic artery flow/kg (ml/min/kg)</td>
<td>4</td>
<td>28.3 ± 2.7</td>
<td>38.3 ± 4.8</td>
</tr>
<tr>
<td>Superior mesenteric artery flow/kg (ml/min/kg)</td>
<td>9</td>
<td>14.6 ± 0.9</td>
<td>16.4 ± 1.6</td>
</tr>
<tr>
<td>External iliac artery flow/kg (ml/min/kg)</td>
<td>4</td>
<td>0.0 ± 0.4</td>
<td>0.2 ± 0.1</td>
</tr>
<tr>
<td>Total peripheral resistance (mm Hg/ml/min) x 100</td>
<td>9</td>
<td>5.4 ± 0.4</td>
<td>5.3 ± 0.2</td>
</tr>
<tr>
<td>Brachiocephalic artery regional resistance (mm Hg/ml/min) x 100</td>
<td>4</td>
<td>25.4 ± 4.0</td>
<td>23.3 ± 4.5</td>
</tr>
<tr>
<td>Superior mesenteric artery regional resistance (mm Hg/ml/min) x 100</td>
<td>9</td>
<td>49.8 ± 4.0</td>
<td>57.2 ± 5.3</td>
</tr>
<tr>
<td>External iliac artery regional resistance (mm Hg/ml/min) x 100</td>
<td>4</td>
<td>131.5 ± 7.6</td>
<td>119.5 ± 8.3</td>
</tr>
</tbody>
</table>

The means ± SEM are given. Statistical significance (all values compared to control): *P < 0.0005, †P < 0.005, ‡P <

Herrick and co-workers (3) found during digestion an increase in blood flow in the superior mesenteric, femoral, and carotid arteries but did not record either blood pressure or cardiac output. Burns and Schenk (4) likewise observed changes in superior mesenteric artery flow during digestion without recording blood pressure. The hemodynamic response pattern during food intake and digestion cannot be properly established unless related systemic hemodynamic variables are recorded simultaneously. A more detailed knowledge of cardiovascular variables related to such basic physiological activities as ingestion and digestion is needed to improve our understanding of various pathophysiological entities. We therefore investigated the systemic and regional hemodynamic responses during food intake and digestion.

Method

Statham electromagnetic flow transducers (Q-series), a catheter, and pneumatic occlusion cuffs (to determine the mechanical zero-flow line) were implanted in two stages under pentobarbital anaesthesia (30 mg/kg, iv). In the first stage, the superior mesenteric artery was dissected retroperitoneally up to 1.5 cm from the aorta. A flow transducer (usually 4 to 5 mm in diameter) was placed around the artery and a pneumatic cuff located distally from the flow transducer. The surgical incision was closed in layers, and the connectors were positioned in the interscapular region. In four dogs an additional flow transducer (4 to 5 mm in diameter) with a pneumatic cuff was also placed around the external iliac artery. The chest was covered with adhesive tape with a pocket for all connectors. In addition, the dogs wore a canvas jacket which covered the leads and catheters.

A second operation was usually performed 1 week later, again under pentobarbital narcosis. A flow transducer (15 to 17 mm in diameter) was placed around the ascending aorta, and the recorded flow (cardiac output less coronary blood flow) was considered as cardiac output; blood pressure was recorded by a tapered Kifa No. 1 catheter implanted into the descending aorta. In four dogs an additional flow transducer (6.0 mm in diameter) was placed around the brachiocephalic artery, and distally to this a silicone-rubber pneumatic cuff was implanted. All com-

Circulation Research, Volume XXIII, December 1968
HEMODYNAMIC CHANGES DURING INGESTION AND DIGESTION

<table>
<thead>
<tr>
<th>Time</th>
<th>Ingestion</th>
<th>1 Hour after feeding</th>
<th>3 Hours after feeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st min</td>
<td>136.3*</td>
<td>±8.7 ±136.3*</td>
<td>±153.6* ±6.8</td>
</tr>
<tr>
<td>2nd min</td>
<td>132.4*</td>
<td>±8.2 ±136.4*</td>
<td>±146.6* ±4.8</td>
</tr>
<tr>
<td>3rd min</td>
<td>126.1*</td>
<td>±1.8 ±126.1*</td>
<td>±137.5* ±3.1</td>
</tr>
<tr>
<td>End ingestion</td>
<td>117.1*</td>
<td>±4.6 ±117.1*</td>
<td>±190.6 ±6.5</td>
</tr>
<tr>
<td>1 Hour after feeding</td>
<td>100 ±4.0</td>
<td>±4.0</td>
<td>±104 ±6.0</td>
</tr>
<tr>
<td>3 Hours after feeding</td>
<td>171.6*</td>
<td>±107.41 ±216.2*</td>
<td>±204.28 ±235.6*</td>
</tr>
</tbody>
</table>

Values were analyzed by the paired t-test. Total peripheral resistance and regional resistances are expressed as mean blood pressure over blood flow (units = mmHg/ml × min⁻¹). Venous pressures in the corresponding vascular beds were not recorded because of difficulties associated with experiments on nonanesthetized animals. Therefore, the mean arterial pressure itself was used instead of the pressure drop across the vascular bed, and the results should be interpreted with this reservation.

Results

Ingestion.—Control values were obtained after the dogs had fasted for 18 hours. A standard canned dog food (450 g) was then brought into the laboratory, and all hemodynamic variables were recorded during ingestion. The actual ingestion of this amount of food usually required some 2 to 3 minutes. The results were monitored as soon as the

0.05. *P < 0.025, **P < 0.001.

nectors and catheter outlets were placed close to the connectors described above. The chest was closed, and the chest tube was withdrawn after about 2 days. All flow transducers were calibrated before implantation using an excised vessel and in situ after killing the dogs.

The experiments were usually carried out 1 week after the last operation and after the dogs had been trained to sit quietly on the table throughout the experiment. The flow transducers were connected to a Statham M 4001 flowmeter. At the beginning and the end of each recording session, standard voltage input was used to standardize the sensitivity of the flowmeter and recorder. The same procedure was used during calibration. Furthermore, the mechanical zero-flow line was established usually at the beginning and the end of measurement. The arterial catheter was connected to a Statham P23 pressure transducer and fastened at heart level to the chest. The pressure and flowmeter outputs were recorded by a Sanborn recorder.

Each day for 3 to 5 days, flows in the ascending aorta, superior mesenteric artery, brachiocephalic artery, and iliac artery, and mean arterial blood pressure were measured. The experiments covered five periods: control, during the anticipation of food, during ingestion, and 1 hour and 3 hours after food intake. Changes in hemodynamic variables relative to the control
dog noticed the presence of food (anticipation period which lasted from 45 to 60 seconds), during the actual ingestion at 1-minute intervals, and 1 minute after the completion of ingestion. The results are summarized in Table 1. Cardiac output rose immediately during the anticipation period (19%) and by the first minute of ingestion it had increased significantly by 42% but then decreased to 41% and 32% 2 and 3 minutes later. A 10% increase in cardiac output persisted after completion of ingestion. The mean arterial blood pressure and heart rate showed a similar response pattern with the changes in rate being the most significant. Cardiac output, heart rate, and blood pressure rose gradually, reaching a maximum in the first minute after ingestion had begun. Total peripheral resistance, on the other hand, showed no significant change, although it tended to drop during the anticipation period and then continued to increase slightly during the second and third minute when cardiac output had already begun to decrease. A modest increase in total peripheral resistance (5%) persisted even after completion of food intake. The above pattern presents an interesting example of blood pressure control involving first a rapid increase in cardiac output, which is then replaced by a more slowly activated vasomotor response of the peripheral vascular bed. Changes in superior mesenteric artery flow during the anticipation period tended to parallel those in total peripheral resistance. During the period of food intake there was a moderate increase in superior mesenteric artery flow, peak values (about +22%) being observed during the second minute. Mesenteric regional resistance was increased by 28% by the third minute. During the anticipatory period and actual ingestion,
HEMODYNAMIC CHANGES DURING INGESTION AND DIGESTION

A significant increase in brachiocephalic artery flow developed and was maintained until the third minute, whereas the flow through the iliac artery increased during the anticipation period but decreased during ingestion to 81% of control in the third minute. Brachiocephalic artery regional resistance and iliac artery regional resistance both decreased during the anticipation period; however, during ingestion iliac artery resistance started to increase, while brachiocephalic artery resistance continued to decrease. The percentage of the cardiac output represented by the superior mesenteric artery flow is significantly lower (7.8% from a control of 8.9%) during the anticipation period. It remains low (7.6%) during the first minute after ingestion has started and continues at this level during the following minutes. The ratio of iliac artery flow to cardiac output was increased slightly during the anticipation period but decreased during ingestion. The ratio of brachiocephalic artery flow to cardiac output was increased during both periods (Fig. 1).

Digestion.—Cardiovascular variables were again measured 1 and 3 hours after completion of food intake, because it was found in preliminary experiments that peak changes seemed to occur in this interval. A summary of the results over this period is shown in Table 1.

During digestion there were no significant changes in blood pressure, cardiac output, heart rate, and total peripheral resistance, whereas superior mesenteric artery flow increased significantly and mesenteric regional resistance decreased correspondingly. At the same time there was an increase in the resistance of the vascular beds supplied by the iliac and brachiocephalic arteries. The pattern of redistribution of blood flow during digestion indicates that a larger proportion of the cardiac output is diverted during digestion into the splanchnic region, while at the same time the ratio of brachiocephalic flow to cardiac output and iliac artery flow to cardiac output are decreased (Fig. 1).

Discussion

Recording of hemodynamic functions on nonanesthetized animals enabled us to monitor these responses under almost natural conditions. Thus the cardiovascular changes during the anticipation period, ingestion, and digestion were analyzed. The hemodynamic responses during ingestion and digestion were found to be significantly different.

Ingestion.—The hemodynamic changes during food intake can be characterized to a certain degree as a generalized sympathomimetic response. This assumption seems to be supported by the fact that in catecholamine-depleted dogs there was no increase in mean arterial blood pressure during food intake (5). Anand and Brobeck (6, 7) have found that the lateral hypothalamic feeding area controls the amount of food which is ingested. On the other hand, amphetamine has an anorexic effect provided that the lateral hypothalamic (8) feeding area is intact. Because amphetamine also produces a sympathomimetic response, it may be assumed that a certain degree of sympathomimetic stimulation may trigger a gradual inhibition of the hypothalamic feeding area and initiate the completion of food intake.

Digestion.—The significant increase in blood flow in the superior mesenteric artery area which occurred during digestion confirms earlier reports (3, 4, 9, 10). On the other hand, our results differ in several respects with regard to the response of the other vascular regions. Herrick et al. (3) observed an increase in carotid and femoral artery flow, whereas in our experiments, blood flow in the brachiocephalic and iliac arteries decreased during digestion. It is possible that this discrepancy may be related to the use by these investigators of the thermostethrometer method which, under certain circumstances, may give quantitatively erroneous results (11).

Reininger and Sapirstein (10) reported that during digestion in rats there was a significant increase in cardiac output which was shared by all of the vascular regions that they examined. They concluded that the increase in
splanchnic blood flow was not the result of a diversion of blood from other vascular areas. In our experiments the increase in cardiac output was not of major significance. On the other hand, a decrease in brachiocephalic and iliac artery flow with a simultaneous significant increase in superior mesenteric artery flow provides evidence of a redistribution of vascular resistances. The differences in the results obtained by Reininger and Sapirstein (10) may be explained by the effects of anesthesia (12) and possibly by the use of different species (rat).

It can be concluded that during ingestion there is a generalized increase in cardiovascular functions expressed by an increase in cardiac output, blood pressure, and heart rate. Brachiocephalic artery flow is increased, representing the increased activity of the corresponding vascular region. Superior mesenteric artery flow changes far less in terms of the total increase in cardiac output than does the brachiocephalic artery flow.

During digestion a significant redistribution of blood supply occurs which favors the splanchnic area coincident with an increased resistance in vascular beds of the brachiocephalic and iliac regions. Cardiac output, mean arterial blood pressure, and total peripheral resistance do not change significantly during digestion.

Acknowledgment
The authors express their appreciation to Dr. B. W. Zweifach for his valuable criticism.

References
Systemic and Regional Hemodynamic Changes during Food Intake and Digestion in Nonanesthetized Dogs
K. FRONEK and L. H. STAHLGREN

Circ Res. 1968;23:687-692
doi: 10.1161/01.RES.23.6.687
Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1968 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org//subscriptions/