THE ABILITY of the sympathetic adrenergic system to modify reflexly splanchnic blood flow and blood volume is well documented.1-5 Francois-Frank and Hallion6 used a plethysmographic technique to demonstrate a decrease in liver blood volume in response to direct and reflex stimulation of hepatic sympathetic nerves in the dog. The technique was modified for use in the cat by Griffith and Emery.7 Liver blood volume decreased during pressor reflexes and increased during depressor reflexes; hemorrhage induced a reduction in liver blood volume. The reactions were abolished on cutting the postganglionic fibers of the hepatic plexus. Further evidence for a reflex control of hepatic capacitance vessels was provided by the studies of Heymans et al.,8 who demonstrated a reduction in liver blood volume during bilateral carotid occlusion in the dog. There is thus considerable evidence for a reflex control of hepatic blood volume mediated through alteration in sympathetic adrenergic nerve activity. However, quantitative measurements could not be made in the above studies.

Recently, Greenway and Oshiro9 reported quantitative measurements of the decrease in liver blood volume during direct stimulation of hepatic nerves in the cat and the dog. Maximal responses were obtained at frequencies of about 6 Hz when 50% of the liver blood volume was expelled. The hepatic capacitance therefore was large and, in contrast to the autoregulatory escape that occurred in the hepatic arterial resistance vessels, the contraction of the capacitance vessels was well sustained through the period of stimulation. However, in the cat, increase in sympathetic vasoconstrictor outflow and blood volume during direct and reflex excitation of the sympathetic nerves.

**Methods**

Dogs weighing 8–22 kg were fasted for 24 hours and were anesthetized with sodium thiopental (15 mg/kg, iv) and α-chloralose (80 mg/kg initially and 10 mg/kg hourly, iv). The dogs were mechanically respired with oxygen at a ventilation rate of 12–14 cycles/min, and the tidal volume was adjusted to give a peak inspiratory pressure between 10 and 12 cm H₂O. When the diaphragm was opened expiratory collapse of the lungs was prevented by immersing the expiratory outflow line in water to a depth of 3–5 cm. Blood Po₂, Pco₂, pH, and hematocrit were measured periodically. If necessary sodium bicarbonate (2–3 ml of an 8.4% solution) was given to maintain pH between 7.3 and 7.4, and the rate of ventilation was adjusted to maintain Pco₂ between 30 and 40 mm Hg. During the surgical preparation of the dog, muscle movement was prevented with gallamine triethiodide, 3 mg/kg, given intravenously. Body temperature was monitored by a telethermometer (Yellow Springs Instrument) placed in the esophagus and maintained between 38°C and 39°C by a water-filled heating blanket.
HEPATIC BLOOD VOLUME

Change in hepatic blood volume was measured with a plethysmograph modified from that described by Greenway et al. The liver was exposed by a bilateral subcostal incision. The contents of the gallbladder were aspirated and the cystic duct was ligated. The central and left lateral lobes of the liver were mobilized by division of their diaphragmatic ligaments and placed within the plethysmograph. The vessels to and from the liver remained intact and were passed through a 3.5-cm aperture which was sealed with a plasticized hydrocarbon gel (Plastibase, Squibb). In the majority of the experiments a small opening was made in the diaphragm to reduce the movement due to inflation of the lungs and thus avoid breaking the Plastibase seal. The plethysmograph was filled with Krebs-Ringer bicarbonate solution at 37°C and connected to the system for recording changes in liver volume. This consisted of a vertical glass cylinder, the liquid surface of which was set at the level of the hilus of the liver. The position of the liquid surface was sensed by a photoelectric cell whose output activated a small motor to raise or lower the glass cylinder and thus maintain constant the pressure within the plethysmograph. The electrical signal from the motor was used to register changes in liver blood volume. A sensitivity of 1 cm of recorded deflection for a 1-ml change in volume was obtained without loss of stability. Eighty percent of the response to a near square wave change in volume was achieved in 1 second.

Placement of the liver within the plethysmograph either did not change portal and hepatic venous pressure or caused an increase of less than 0.5 cm of H2O.

HEPATIC BLOOD PRESSURE

Portal venous pressure was recorded by a small catheter inserted into the pancreaticoduodenal vein and advanced into the substance of the liver. Hepatic venous pressure was recorded from a catheter introduced into the left jugular vein and positioned within the liver from the inferior vena cava. An attempt was made to position the tip of the catheter in one of the small hepatic veins, because it has been shown that stimulation of the sympathetic nerves causes constriction of the hepatic venules but not of the large hepatic veins. This was not possible in all experiments, because in some instances when the catheter was advanced to the recommended distance of 4 cm from the hepatic-inferior caval junction it was not possible to sample blood freely. Hepatic arterial pressure was estimated from the pressure recorded by a catheter inserted into the femoral artery and advanced to the level at which the celiac and superior mesenteric arteries leave the aorta. The arterial blood pressure at this point was similar to that obtained from a catheter inserted into the common hepatic artery from the divided end of the gastroduodenal artery. The level of the right atrium was taken as the zero reference point for all blood pressures.

At the end of the experiment the dog was exsanguinated. The intrahepatic position of the catheter tip was determined, and the portions of the liver within and outside of the plethysmograph were weighed separately.

HEPATIC BLOOD FLOWS

Blood flow in the hepatic artery and the portal vein was measured with a square wave electromagnetic flowmeter (Carolina Medical Electronics) and noncannulating flow transducers. When only hepatic blood flow and blood pressures were measured a right subcostal incision was used; when both hepatic blood flow and blood volume were measured a bilateral subcostal incision was made.

A 5-mm length of the common hepatic artery was dissected free from its connective tissue sheath and from surrounding nerves about 1 cm distal to the celiac ganglion. A snugly fitting noncannulating flow transducer was applied to the artery. A similar short section of the artery was dissected distal to the flow transducer to allow placement of an occluding snare. The gastroduodenal and right gastric arteries were ligated to make sure that only hepatic arterial flow was measured. At the end of the experiment the common hepatic artery was dissected to display the proper hepatic arteries and confirm that the blood passing through the flow transducer went only to the liver. In three dogs hepatic arterial flow was recorded with a cannulating as well as a noncannulating flow transducer. The latter unit was removed after the initial observations, and blood from the renal artery was pumped at constant pressure through a cannulating flow transducer into the distal end of the divided hepatic artery. The portal vein between the gastrosplenic and pancreaticoduodenal veins was dissected free just enough to allow placement of a noncannulating flow transducer. An occluding snare to obtain zero flow was positioned downstream from the ligated pancreaticoduodenal vein. Any small venous branch joining the portal vein between the flow transducer and the liver was ligated. At the end of the experiment the portal vein was dissected to verify the absence of patent branches other than the right and left portal hilar veins.

Both flow transducers were calibrated in situ at the end of each experiment. The vessel was cannulated above and below the transducer and connected to a pump reservoir system filled with the dog's own blood. Timed volume collections were made over the range of flows observed during the experiment.

Hepatic blood flows, blood pressures, and change in hepatic blood volume were recorded with an ultraviolet oscillograph (Honeywell Visicorder).

PREPARATION OF THE ANIMAL

Carotid Sinus Baroreceptors

The carotid sinuses were isolated bilaterally using a modified Moissejeff technique and perfused with Krebs-Ringer bicarbonate solution that had been equilibrated with a gas mixture of 95% O2 and 5% CO2. The pH was adjusted to 7.4. A pressure control system allowed the pressure within the vasa vasorum to be maintained constant at any desired value. The carotid chemoreceptors were excluded from the vascularly isolated region by ligation of the occipital arteries at their origin from the external carotid arteries. Both vagi were sectioned in the neck to denervate the aortic arch baroreceptors and the cardiopulmonary mechanoreceptors.
Cardiopulmonary Mechaneoreceptors

The influence on hepatic blood volume of cardiopulmonary receptors subserved by vagal afferents was assessed from the response to reversible cold block of both cervical vagal nerves in dogs with the aortic and cervical sympathetic nerves cut bilaterally and the carotid sinuses vascularly isolated and maintained at a constant low pressure. Atropine (0.2 mg/kg per hour, iv) was given to block the vagal cardiac efferent nerves. Several studies have shown that in dogs so prepared the cardiovascular responses to vagal cold block reflect the vasomotor inhibition exerted by vagal afferents from the cardiopulmonary region prior to the block.16

Electrical Stimulation of Hepatic Nerves

The sheath of nerves enmeshing the hepatic artery was divided below the celiac ganglion and freed for a distance of 1 cm. The distal freed end of the nerve bundle was drawn through bipolar insulated platinum ring electrodes. The hepatic sympathetic adrenergic nerves were electrically stimulated with rectangular pulses of 15 V, 3-5 msec in duration, and frequencies between 0.5 and 30 Hz (Grass stimulator, model SDS). Stimulation was continued for 2 minutes or until a steady state was reached; an interval of 10-15 minutes was allowed between tests.

PROTOCOL AND DATA ANALYSIS

The changes in hepatic blood volume, blood pressure, and blood flow were measured during (1) exposure of the vascularly isolated carotid sinuses to different constant nonpulsatile pressures, (2) electrical stimulation of the hepatic nerves at different frequencies, and (3) cold block of the cervical vagal nerves at different constant nonpulsatile pressures within the isolated carotid sinus.

The responses to the various procedures were measured as soon as steady values were obtained. The observations in each dog were summed to obtain the mean and SE for the group. The statistical significance of the difference in the means was evaluated by Student's t-test for paired observations. The level of significance was taken as 0.05.

Results

EFFECT OF CHANGES IN CAROTID SINUS PRESSURE ON HEPATIC BLOOD VOLUME

In 16 dogs increases in hepatic blood volume which ranged from 3.6 to 11.7 ml/100 g immediately followed the abrupt increase in pressure from 40 to 240 mm Hg in the isolated carotid sinus. At these pressures carotid sinus baroreceptor inhibition is, respectively, absent or minimal, and maximal.17 The change in volume was rapid, with 80% of the maximal response occurring in a mean time of 25 seconds, and the volume taken up was retained during the 2-3 minutes of observation. The increase in sinus pressure was repeated four to five times in each dog and a similar volume of blood generally was taken up during each test. The coefficient of variation (sd/mean change × 100) ranged from 6% to 38%, with a mean of 18%. The mean volume (± se) of blood taken up by the livers was 7.2 ± 0.7 ml/100 g, or 23% of liver blood volume calculated as 31 ml/100 g.9 Portal and hepatic venous pressure decreased, respectively, by 4.0 ± 0.6 and 2.1 ± 1.7 cm H2O. Arterial blood pressure decreased by 127 ± 7.2 mm Hg. In these experiments the hepatic venous catheter was located 4 cm or more from the junction with the inferior vena cava.

The mean weight of the liver in this series was 260 ± 12 g, 70% of which was contained within the plethysmograph.

In 10 of the 16 dogs the increase in sinus pressure was repeated after the liver had been denervated by section of the sheath of nerves encircling the hepatic artery. In each instance hepatic denervation attenuated the increase in liver blood volume previously observed. The mean change in hepatic blood volume of 2.8 ± 0.5 ml/100 g after denervation was significantly different from the control value of 7.3 ± 0.8 ml/100 g. The decreases in arterial blood pressure were, respectively, 128 ± 9 mm Hg and 112 ± 11 mm Hg, values not significantly different.

In nine other dogs the pressure within the carotid sinus initially was set equal to the systemic arterial pressure recorded before the sinus was vascularly isolated. Intrasinus pressure then was increased or decreased in random fashion in steps of 20 mm Hg, until the range of 40-240 mm Hg had been covered. Figure 1 is a reproduction of a record obtained during one of these experiments. On reducing the carotid sinus pressure to 40 mm Hg (upper panel) there was a rapid decrease in hepatic blood volume and an increase in aortic, portal vein, and hepatic vein pressures. Oppositely directed changes occurred when the carotid sinus pressure was increased in random fashion in steps of 20 mm Hg (lower panel). The scale for change in liver blood volume thus shows only the magnitude and not the direction of movement of blood. Abbreviations used in the lower panel are identified in the upper panel.
suddenly increased to 240 mm Hg from the control level of 171 mm Hg. The rhythmic changes in hepatic volume of 8 ml induced by inflation and deflation of the lungs were not affected during the release or uptake of blood by the liver.

Figure 2 shows the mean stimulus response curve for arterial blood pressure and hepatic blood volume for the nine dogs. Both curves are sigmoid in shape and symmetrical about the mean control carotid sinus pressure of 148 ± 4.7 mm Hg. The steepest slope was between 30 mm Hg above and 30 mm Hg below the control carotid sinus pressure. A mean decrease in hepatic blood volume of 4.8 ± 0.8 ml/100 g and a mean increase in arterial blood pressure of 77 ± 11 mm Hg was recorded during maximal carotid sinus hypotension. Comparable figures for maximal sinus hypertension were an increase in volume of 6.3 ± 0.3 ml/100 g and a decrease in pressure of 90 ± 4 mm Hg. The mean changes in hepatic blood volume represent, respectively, 16% and 20% of the calculated hepatic blood volume. Using the linear part of the slope, the change in hepatic blood volume per mm Hg change in carotid sinus pressure was calculated as a percentage of the total change in volume. The change in arterial pressure per mm Hg change in sinus pressure, over the same range, was expressed similarly. Calculated in this manner, the gains of the two systems were similar.

The curves relating the changes in portal and hepatic venous pressure to the pressure within the carotid sinus were similar in shape to those of arterial blood pressure. At a carotid sinus pressure of 40 mm Hg, the mean increase in portal and hepatic vein pressure, respectively, was 3.2 ± 0.6 cm H2O and 1.0 ± 0.3 cm H2O from mean control values of 7 ± 0.8 cm H2O and 1.2 ± 0.5 cm H2O; mean decreases in venous pressure of 2.0 ± 0.2 cm H2O and 0.8 ± 0.3 cm H2O, respectively, were recorded at a carotid sinus pressure of 240 mm Hg. In these experiments the tip of the hepatic vein catheter was located 4 cm or more from the inferior vena cava junction. The mean weight of the liver in this group of experiments was 347 ± 21 g, 68% of which was contained within the plethysmograph.

In each experiment of the above three series, hepatic blood volume and blood pressures returned to the control values when the pressure within the carotid sinus was returned to the initial level.

Changes in liver blood volume were measured in two of the dogs during temporary occlusion of the portal vein and the hepatic artery by previously placed snares. The right gastric and the pancreaticoduodenal arteries had been ligated. Mechanical interruption of hepatic inflow reduced liver blood volume by 3.8 ml/100 g and 3.1 ml/100 g in one dog and by 2.1 ml/100 g and 2.9 ml/100 g in the other. During the first interruption of hepatic inflow, when liver blood volume had stabilized at the reduced value, carotid sinus pressure was reduced to 40 mm Hg. Liver blood volume was decreased by 4.5 ml/100 g and 6.3 ml/100 g, respectively. Increase in carotid sinus pressure to 240 mm Hg during the second period of flow interruption increased hepatic blood volume by 4.2 ml/100 g and 3.6 ml/100 g, respectively.

**EFFECT OF ELECTRICAL STIMULATION OF HEPATIC NERVES ON HEPATIC BLOOD VOLUME**

In each of the 14 dogs studied hepatic blood volume decreased rapidly in response to electrical stimulation of the hepatic nerves, and the reduction in hepatic blood volume was maintained for as long as 10 minutes of stimulation. The mean weight of the liver in this group of experiments was 259 ± 14 g, of which 72% was contained within the plethysmograph. Figure 3 is a reproduction of a recording made during stimulation of the hepatic nerves at 15 Hz; 80% of the total decrease in hepatic volume of 35 ml was achieved in 42 seconds but almost 5 minutes were required for hepatic volume to return to the control value after cessation of stimulation (not shown). Respiratory fluctuations in hepatic volume were decreased during nerve stimulation. Portal pressure increased by 19 cm H2O and the increase in hepatic vein pressure was 1.2 cm H2O. The curve relating the mean decrease in hepatic blood volume to the stimulus frequency was parabolic, the response becoming maximal at a frequency of 15 Hz. At this frequency 80% of the maximal response was com-
completed in a mean time of 19 seconds. The mean maximal decrease in hepatic blood volume was 18.6 ± 1.6 ml/100 g, corresponding to 60% of calculated liver blood volume. At this level of excitation (15-20 Hz) portal venous pressure increased by a mean of 10 ± 2 cm H2O from a mean control value of 9.6 ± 0.7 cm H2O.

Of the three dogs in which hepatic vein pressure was measured during electrical stimulation of the hepatic nerves, the catheter tip was situated in a major hepatic vein at a point 3.5 cm from the inferior vena cava junction in one dog (Fig. 3). In the other two dogs the catheter tip was 4.5 and 5.5 cm distant from the inferior vena cava junction. The increases in hepatic vein pressure during maximal electrical stimulation of the hepatic nerves were 4 and 6.3 cm H2O, respectively. Corresponding values for the increases in portal vein pressure were 8 and 18 cm H2O.

**EFFECT OF CHANGES IN CAROTID SINUS PRESSURE ON HEPATIC BLOOD FLOWS AND RESISTANCES**

Increases and decreases in carotid sinus pressure, made in random fashion and in steps of 20 mm Hg from a pressure set equal to the control arterial blood pressure, caused decreases and increases, respectively, in hepatic arterial and portal venous vascular resistance. Mean data from six dogs are shown in Figure 4. The stimulus-response curves are sigmoid and symmetrical about the control value of carotid sinus pressure. At a carotid sinus pressure of 40 mm Hg hepatic arterial blood pressure increased by 81 ± 13 mm Hg from a mean control of 140 ± 10 mm Hg. Hepatic arterial blood flow increased by 6.4 ± 4.5 ml/100 g per min from a mean control of 39 ± 7 ml/100 g per min. Portal pressure increased by 2.1 ± 0.5 mm Hg from a mean control of 7.4 ± 0.5 mm Hg. Portal flow increased by 1.1 ± 3.1 ml/100 g per min from a mean control of 80 ml/100 g per min. Hepatic venous pressure increased by 0.6 ± 0.2 mm Hg from a mean control of 1.8 ± 0.5 mm Hg. In these experiments the tip of the hepatic vein catheter was situated within 4 cm of the junction of the hepatic vein with the inferior vena cava. Hepatic arterial and portal venous resistances increased by 45% and 22%, respectively, from their control values.

At a sinus pressure of 240 mm Hg, hepatic arterial blood pressure and blood flow, respectively, decreased by 68 ± 8 mm Hg and 3.8 ± 3.1 ml/100 g per min. Portal pressure and portal blood flow decreased, respectively, by 1.2 ± 0.2 mm Hg and 3.5 ± 2.5 ml/100 g per min. Hepatic venous pressure decreased by 0.2 ± 0.1 mm Hg. Hepatic arterial and portal venous resistances decreased by 44% and 18%, respectively, from their control values.

In these experiments hepatic arterial and portal venous resistances changed in the direction anticipated from an increase or decrease in carotid sinus pressure. The direction of change in liver blood flows relative to change in carotid sinus pressure, however, was less predictable. In four of the six dogs hepatic arterial blood flow changed in the same direction as arterial blood pressure. The mean increases and decreases in blood flow were 35% and 20% of the mean control blood flow of 39 ml/100 g per min. In two dogs hepatic arterial blood flow decreased by 10% and 13% during maximal sinus hypertension and increased by 7% and 13% during maximal sinus hypotension. During carotid sinus hypotension portal blood flows were slightly increased in three dogs, unchanged in two dogs, and slightly decreased in one dog. During sinus hypertension portal blood flow was slightly decreased in four dogs, was unchanged in one dog, and slightly increased in one dog. When the direction of the change in portal blood flow was disregarded, the mean change during maximal sinus hypotension and hypertension was 9.6% of the mean control blood flow of 80 ml/100 g per min.

To confirm the hepatic arterial vasoconstrictive and vasodilator responses to change in carotid sinus pressure, the hepatic artery was cannulated in three of the six dogs and perfused at a constant nonpulsatile pressure of 120 mm Hg. Hepatic arterial inflow was measured with a cannulating flow transducer. All three dogs showed decreases in hepatic arterial blood flow as carotid sinus pressure was reduced from the control value and increases as sinus pressure was increased above control. At a sinus pressure of 40 mm Hg the percent decreases in flow from the mean control flow of 61 ml/100 g per min were, respectively, 7%, 10%, and 18%; corresponding increases during a sinus pressure of 240 mm Hg were 7%, 11%, and 21%. The increases and decreases in hepatic arterial flow were sustained throughout the 2- to 3-minute test period.

The mean weight of the liver in this group of dogs was equal to 460 ± 22 g.

In three other dogs hepatic blood flows, blood pressures, and change in hepatic blood volume were recorded simultaneously during changes in carotid sinus pressure. An example of a recording made during exposure of the vascularly isolated carotid sinus to a pressure of 30 mm Hg (upper panel) and 250 mm Hg (lower panel) is shown in Figure 5. During sinus hypotension both hepatic arterial and portal venous flow increased by 45 and 20 ml/min, respectively, and hepatic blood volume de-
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Flow

FIGURE 5 Reproduction of original tracing showing simultaneously recorded changes in liver blood volume, hepatic arterial and portal venous flows and pressures, and hepatic vein pressure during carotid sinus hypotension (upper panel) and hypertension (lower panel) in an anesthetized dog with vagi cut. Immediately following reduction in sinus pressure there was a transient decrease of 20 ml/min in hepatic arterial blood flow and increase of 20 ml/min in portal vein flow. Hepatic arterial blood subsequently increased and stabilized at 45 ml/min, above the control level; the initial increase in portal flow was sustained. Total liver blood flow was increased by 65 ml/min; total liver blood volume decreased by 16 ml. Sinus hypertension was followed by an immediate and sustained decrease in both inflows. Total liver blood flow decreased by 195 ml/min; total liver blood volume increased by 10 ml.

creased by 11 ml. During sinus hypertension hepatic arterial and portal venous flows decreased, respectively, by 100 and by 95 ml/min and hepatic blood volume increased by 10 ml.

The changes in arterial pressure, hepatic blood volume, and portal venous and hepatic arterial blood flow and resistance during graded changes in carotid sinus pressure of one of the three dogs are shown in Figure 6. Similar responses were obtained in the other two dogs. The point of interest is that as carotid sinus pressure is increased or decreased above and below the control level of 160 mm Hg, hepatic blood volume is increased and decreased, respectively, despite oppositely directed changes in total hepatic blood flow.

EFFECT OF INTERRUPTION OF CARDIOPULMONARY VASOMOTOR INHIBITION ON HEPATIC BLOOD VOLUME

The effect of interrupting vagal afferent traffic from the cardiopulmonary receptors at different carotid sinus pressures was examined in seven dogs. Responses from one dog representative of the group are shown in Figure 7. At the control carotid sinus pressure of 145 mm Hg, vagal cold block resulted in a decrease in hepatic blood volume of 1.8 ml/100 g, no change in portal venous pressure, and an increase of 10 mm Hg in arterial blood pressure. At sinus pressures of less than 145 mm Hg, vagal block caused an increase in portal pressure and larger increases and decreases in aortic blood pressure and hepatic blood volume, respectively. The responses to vagal cold block were maximal at a sinus pressure of 40 mm Hg. At carotid sinus pressures of 160 mm Hg and greater, vagal cold block was without effect. A similar pattern of response was shown by the other six dogs. At carotid sinus pressures greater than 180 mm Hg, vagal cold block was ineffective in changing portal pressure or hepatic blood volume; maximal responses to vagal block were obtained at carotid sinus pressures of 100 mm Hg and less.

The effect on hepatic blood volume of withdrawal of inhibitory traffic from the carotid sinus and the cardiopulmonary receptors was compared among these seven dogs by reducing carotid sinus pressure from 220 to 40 mm Hg and then cold-blocking the vagi. The grouped data are shown in Figure 8. In each dog withdrawal of carotid sinus inhibition caused a greater increase in aortic blood pressure and decrease in hepatic blood volume than did the subsequent interruption of cardiopulmonary inhibition (Fig. 8, left). Combined withdrawal of carotid sinus and cardiopulmonary inhibitory traffic reduced hepatic blood volume by a mean of 13 ml/100 g. The carotid sinus was responsible for 63% of this total change and the cardiopulmonary receptors for 37% (Fig. 8, right).

Discussion

This study confirms the earlier reports that changes in hepatic blood volume result from direct and reflex alteration in activity of the hepatic sympathetic nerves. The measurements indicate that the translocations of blood are substantial and are in agreement with the conclusion of Greenway et al.9,18 that the liver is an important blood reservoir. In their study the maximum volume expelled decreased by 11 ml. During sinus hypertension hepatic arterial and portal venous flows decreased, respectively, by 100 and by 95 ml/min and hepatic blood volume increased by 10 ml.

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from the dog liver during nerve stimulation represented 36% of hepatic blood volume; in our present study the corresponding value was 60%. This difference is partly due to the use of a mean figure for hepatic blood volume in this study and partly to the expulsion of a greater absolute volume of blood. In the study by Greenway and Oshiro, the maximum volume expelled was calculated to equal a total volume release of 3.9 ml/kg of body weight; in our present experiments the corresponding figure was 4.9 ml/kg. The use of chloralose instead of sodium pentobarbital anesthesia and of somewhat larger dogs (9.9 kg against 7.3 kg) may have contributed to this difference.

Change in vascular tone of the hepatic capacitance vessels by the carotid baroreflex also resulted in the uptake and release of considerable volumes of blood. During maximal sinus hypertension the total volume of blood taken up by the liver was calculated to be 22 ml, or 1.6 ml/kg; during sinus hypotension a total volume of 17 ml, or 1.2 ml/kg, was expelled. This last was equal to 26% of the mean maximal volume released from the liver during electrical stimulation of the hepatic nerves. The uptake and release of blood was rapid, the major portion of the shift of blood being accomplished in 30-40 seconds. The reflex mean decrease in hepatic blood volume during carotid sinus hypotension was less than the mean increase during sinus hypertension. This probably was a reflection of the control level of sympathetic tone, since the vasoconstrictor response of arterial blood pressure was less than the vasodilator.

 Interruption of vasomotor inhibition from the cardiopulmonary receptors had its maximal effect on hepatic blood volume when the influence of the carotid baroreflexes was minimal or absent. The mean decrease in hepatic blood volume was 4.8 ml/100 g, or 15% of the total liver blood volume. Vagal block was without effect on hepatic blood volume or systemic arterial pressure at carotid sinus pressures of 160 mm Hg and greater. The interaction of carotid and cardiopulmonary baroreflexes on the hepatic capacitance vessels is thus similar to that reported for the systemic resistance vessels. In regard to the degree to which cardiopulmonary receptors can modulate, in different vascular areas, the vasoconstriction due to withdrawal of carotid sinus vasomotor inhibition, the response of the liver is between that of skeletal muscle and kidney. If the vasomotor response to combined withdrawal of carotid and cardiopulmonary inhibition is set equal to 100%, the cardiopulmonary receptor contribution in the hindlimb is 20%, in the kidney 50%, and in the liver 37%. This ability of cardiopulmonary receptors to modify the response of the hepatic capacitance vessels to withdrawal of carotid sinus inhibition may in part explain the failure of Lautt and Greenway to obtain a reduction in liver blood volume in the cat during carotid occlusion. This explanation is supported by the finding that, in the cat, bilateral carotid occlusion can give rise to an increase in discharge frequency of cardiac vagal afferents.

That the efferent arm of the reflex response of the liver to change in carotid sinus pressure is the hepatic sympathetic nerves is shown by the attenuated response following section of the postganglionic fibers of the hepatic plexus. Further, two sets of observation indicate that the baroreflex-mediated changes in hepatic blood volume primarily are due to increase and decrease in sympathetic tone of the hepatic capacitance vessels and are not passive responses to change in blood flow to the liver. In the experiment shown in Figure 5 hepatic arterial and portal venous blood flows each were reduced, respectively, by 100 and by 95 ml/min during carotid hypertension. It would be anticipated that this considerable reduction in total hepatic blood flow (34% of control flow) would result in a passive decrease in liver blood volume. The measured response was an uptake of 10 ml. In seven of the nine dogs in which blood flow was recorded, the direction of the change in hepatic arterial and portal venous blood flow during change in carotid sinus pressure was opposite to that of the anticipated or recorded change in liver blood volume. If the grouped data from the nine dogs are expressed in terms of total liver blood flow, this increased and decreased, respectively, by means of 10.9% and 12.1% from the mean control of 115 ml/100 g per min during maximal carotid sinus hypo- and hypertension. The
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reflex induced changes in liver blood flow thus would tend to oppose rather than enhance the simultaneous changes in liver blood volume.

Further, following total interruption of blood flow to the liver in two dogs, carotid sinus hypertension resulted in respective increases in liver blood volume of 12% and 14% and decreases of 15% and 20% during sinus hypotension. Thus, with regard to its function as a blood reservoir the liver can take up or release volumes of blood in the absence of, or independently of, changes in blood flow.

As indicated, in almost all the experiments hepatic arterial perfusion pressure was free to change in response to alteration in carotid sinus pressure. The changes in hepatic arterial and portal venous resistance were in the direction anticipated from increase and withdrawal of carotid baroreceptor inhibition. However, the respective levels of blood flow appeared to be determined by the existing systemic arterial blood pressure and generally changed in the same direction. When hepatic arterial perfusion pressure was maintained constant, hepatic arterial blood flow decreased and increased, respectively, during carotid sinus hypotension and hypertension. The changes were less than 20% of control levels but were sustained for the period of observation.

In a previous study in which systemic arterial pressure was maintained constant, flow blood in the superior mesenteric and the celiac artery also increased and decreased, respectively, during carotid sinus hypotension and hypertension. A transient peak change in blood flow was followed by a sustained flow greater or lesser, respectively, than the control blood flow. Partial recovery of hepatic arterial and portal venous blood flows from the vasoconstrictive action of hepatic sympathetic nerve stimulation in the dog also was reported by Hanson.31 After 5–6 minutes of stimulation blood flow recovered to a stable level which was 60% of the initial reduction in flow. Hepatic nerve stimulation was found by Greenway and Oshiro9 to cause a frequency-dependent sustained reduction in hepatic arterial inflow in dogs. In contrast, hepatic arterial vasoconstriction is not well maintained in the cat. Occlusion of the carotid arteries in this animal caused a rise in arterial blood pressure with little change in hepatic artery blood flow; when hepatic artery pressure was controlled at the precocclusion level, the blood flow showed an abrupt decrease followed by a recovery toward control level.31 Also, electrical stimulation of the hepatic sympathetic nerves resulted in a decrease in hepatic arterial flow which was not maintained, and autoregulatory escape occurred.31

Thus in the dog sustained alterations in hepatic arterial blood flow and liver blood volume result from direct or reflex excitation of the hepatic sympathetic nerves. In the cat the changes in hepatic arterial flow are small or are not sustained throughout the period of stimulation. Carotid occlusion in the cat was not accompanied by significant changes in liver blood volume, although electrical stimulation of the hepatic nerves resulted in a marked frequency-dependent decrease in hepatic volume which was well maintained.

In the cat and in the dog it has been shown that the terminal portion and junction of the hepatic veins with the inferior vena cava did not constrict during excitation of the hepatic sympathetic nerves.14,34 The observations in our present study regarding the relation of the change in hepatic vein pressure to the depth to which the catheter is inserted into the vein are in accord with the previous findings. The uptake and release of blood from the liver thus is controlled by the vascular tone of the portal and hepatic venules and not by hepatic vein sphincters.

The present studies were conducted in anesthetized dogs with a bilateral subcostal incision, and the values obtained could have been influenced by the surgical procedures. If so it would most likely be to reduce rather than augment the induced changes in hepatic blood volume. In contrast to the findings obtained in the conscious dog by Guntheroth and Mullins,31 our present study and the work of Greenway and Lister14 would suggest that the liver has a significant role as a blood reservoir. Uptake and release of blood are well maintained throughout the period of stimulation, and the changes in blood volume are largely independent of changes in blood flow to the liver. The volume of blood mobilized is substantial, and the translocation is rapid, and may thus contribute to the reflex control of the circulation effected through the arterial baroreceptors and the cardiopulmonary receptors.

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References

3. Grayson J, Mendel D: Physiology of the Splanchnic Circulation. Balti-
more, Williams & Wilkins, 1965
ington, D. C., American Physiological Society, 1963, pp 1387–1438
6. Francois-Frank Ch-A, Hallion L: Recherches experimentales sur
l innervation vaso-constrictive du foie (3 e Memoire Reflexes Vaso-
Constricteurs). Arch Physiol Norm Pathol (S5) 9: 434–447, 1897

15. Grayson J, Mendel D: Physiology of the Splanchnic Circulation. Balti-
more, Williams & Wilkins, 1965
ington, D. C., American Physiological Society, 1963, pp 1387–1438
18. Francois-Frank Ch-A, Hallion L: Recherches experimentales sur
l innervation vaso-constrictive du foie (3 e Memoire Reflexes Vaso-
Constricteurs). Arch Physiol Norm Pathol (S5) 9: 434–447, 1897
Regional Myocardial Function and Dimensions Early and Late after Myocardial Infarction in the Unanesthetized Dog

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SUMMARY Pairs of ultrasonic dimension gauges and a micro-manometer implanted in the subendocardium of the left ventricles of unanesthetized dogs were used to analyze serial changes in hemodynamic status and segmental function for up to 4 weeks after permanent circumflex coronary artery occlusion. Regional function was studied in control segments and in segments identified as marginal (hypokinetic) and ischemic. In three dogs, after transient regional dysfunction, no myocardial infarction developed, whereas in five dogs regional dysfunction at 3 hours after occlusion was followed by the development of persistent dysfunction and infarction. Left ventricular end-diastolic segment length (EDL) changes over time; EDL of the control segments increased progressively, but in marginal segments EDL was 12% below control and in the ischemic segments 30% below control by 4 weeks. Progressive increases in percent active shortening occurred in control segments, but holosystolic bulging was replaced by akinesia in ischemic segments, and persistent reduction in shortening was present in marginal segments at 4 weeks. Correlations were found between percent scar and reduction in shortening. EDL, and the ratio of change in diastolic length to change in diastolic pressure. These methods have detected hyperfunction in normal regions and variable segmental loss of contractile function, together with reduction of subendocardial dimensions and changes that may reflect decreased diastolic compliance in ischemic regions. We conclude that this model for the conscious animals may be useful for studying the influence of therapy on the extent of myocardial damage after experimental coronary occlusion.

USING AN external dimension gauge, Tennant and Wiggers' first documented the development of a systolic bulge in the ischemic region very early after coronary occlusion. Recent studies on regional myocardial function using pairs of miniature ultrasonic crystals implanted in the left ventricular subendocardium in both open-chest and chronically instrumented, unanesthetized dogs have confirmed the rapid development of holosystolic expansion in the central ischemic area, accompanied by reduced active shortening in adjacent marginal myocardial segments and by augmented shortening in distant, normal regions. However, the subsequent time course and character of changes in regional segment function and dimensions after permanent coronary occlusion have not yet been elucidated. In the days and weeks after myocardial infarction, changes such as edema, tissue necrosis, and hypertrophy, in addition to ischemia, should have important effects on regional muscle shortening and diastolic properties. Information concerning such changes could have considerable significance relative to our understanding of factors that influence cardiac function in the recovery phase after coronary occlusion, as well as relative to the development of models...
Change in liver blood flow and blood content in dogs during direct and reflex alteration of hepatic sympathetic nerve activity.

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