Role of Cardiac, Pulmonary, and Carotid Mechanoreceptors in the Control of Hind-Limb and Renal Circulation in Dogs

By Giuseppe Mancia, John T. Shepherd, and David E. Donald

ABSTRACT

Reflex control of hind-limb and renal resistance vessels by cardiac and pulmonary receptors was studied by interrupting afferent vagal nerve traffic when only the heart or only the lungs were in situ in anesthetized dogs with sinoaortic denervation. During normocapnia, interruption of cardiac and of pulmonary vagal traffic decreased hind-limb blood flow (constant-pressure perfusion) by 23% and 21%, respectively. Corresponding decreases in renal blood flow were 23% and 33%. Hypercapnia augmented the decreases in renal blood flow due to the vagal block. Thus, the inhibitions exerted by the heart and lung receptors on these two beds were similar during normocapnia but were greater on the renal vessels during hypercapnia. In closed-chest dogs with their aortic nerves sectioned and their carotid sinus pressure controlled, combined withdrawal of carotid and cardiopulmonary inhibition decreased hind-limb and renal blood flow by about 80% and 40%, respectively, during both normovolemia and hypervolemia. Interruption of cardiopulmonary inhibition was responsible for 17% and 31% of the decrease in hind-limb blood flow at normal and increased blood volumes, respectively; values for the decreases in renal blood flow were 50% and 65%. Thus, cardiopulmonary receptors oppose the vasoconstriction due to carotid sinus hypotension more effectively in the kidney than they do in the hind limb.

In recent years, the control of muscle and renal circulations by different reflexogenic areas has received much attention. In cats (1-4) and dogs (5, 6), a change in carotid mechanoreceptor activity has a greater effect on muscle resistance vessels than it does on renal resistance vessels. When inhibitory traffic from the cardiopulmonary receptors is interrupted by vagal cooling (3) or decreased by hemorrhage (4, 5, 7) in cats (3, 4), rabbits (7), or dogs (5), the constriction of renal resistance vessels is greater than that of muscle resistance vessels. Direct comparisons of carotid and cardiopulmonary inhibitory influences in cats have shown that carotid occlusion consistently leads to more pronounced hind-limb responses than does vagal cooling; the opposite occurs for the renal responses (3). A major functional role has been ascribed to cardiac receptors by Öberg and White (3, 4), who have found that, in cats, the renal and the hind-limb responses to vagal cooling or hemorrhage are greatly decreased after section of the cardiac nerves. However, Ott et al. (8, 9) have shown in rabbits that the lung depressor reflex is responsible for opposing the increase in renal and hind-limb vascular resistance caused by the action of carbon dioxide at the vasomotor center.

These studies suggest that it is important (1) to compare, in the same species, the separate roles of the receptors in the heart and the lungs in the inhibitory control of hind-limb and kidney vessels during normocapnia and hypercapnia and (2) to extend the comparison of carotid and cardiopulmonary inhibitory influences by utilizing the full range of activity of the former and increasing the activity of the latter by augmenting the blood volume.

Methods

Twenty-nine dogs were anesthetized with sodium thiopental (15 mg/kg, iv) and chloralose (80 mg/kg initially and 10 mg/kg hourly, iv), paralyzed with gallamine triethiodide (3 mg/kg hourly, iv), and mechanically ventilated. Heparin was given prior to cannulation of blood vessels (2.5 mg/kg initially and 1 mg/kg hourly, iv). The vagal efferent cardiac nerves were blocked with atropine (0.2 mg/kg hourly, iv). Both the right and left aortic nerves and cervical sympathetic nerve trunks were divided (10). Section of the cervical aortic nerves results in acute loss of the chemoreflex and the baroreflex from the aortic arch and the major intrathoracic arteries (10-15). Further proof of acute loss of the aortic baroreflex was afforded in the present study by the failure of vagal blockade to elicit an increase in systemic vascular resistance after removal of the heart and lungs.

Thermodes were applied to the vagal nerves and per-
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fused with cold alcohol until a temperature of -1°C was registered at the surface of the nerve; the block was reversed by perfusion with water at 37°C. The effectiveness of the block was demonstrated by the absence of vascular changes when the vagi were severed caudal to the thermodes.

Measurements.—Aortic blood pressure and, in open-chest dogs, right and left atrial pressures were measured through catheters connected with strain-gauge transducers (Statham P23D). Mean blood pressure was obtained by electronic damping of the pulsatile signal. Respiratory pressures were measured with a strain-gauge transducer (Statham PM5d) connected to a side arm of the cuffed tracheal tube. The left kidney and either the left or both hind limbs were perfused at a constant nonpulsatile pressure of 120 mm Hg with oxygenated blood obtained from an extracorporeal circuit or the brachial artery. Because the perfusion pressure was constant, the changes in blood flow reflected changes in vascular resistance.

The abdominal aorta was cannulated in a cephalad direction distal to the origin of the left renal artery and in a caudad direction central to the origins of the external iliac arteries and perfused from the common outlet of the servocontrolled blood-flow pump. Heat exchangers maintained the blood temperature at 37°C. To eliminate other sources of blood to the hind limbs and the left kidney, the lumbar arteries originating along the exposed aortic segment, the deep circumflex iliac and inferior mesenteric arteries, the terminal aorta, and the aorta above the origin of the left renal artery were ligated.

Blood flows were measured with cannulating electromagnetic flow probes (Carolina Medical Electronics). Zero-flow signals were recorded while both circulations were maintained through bypass lines. The flow probes were calibrated at the end of the experiment using the dog's own blood and a pump-reservoir system.

Separate Roles of Cardiac and Pulmonary Receptors.—To allow full manifestation of the vasomotor inhibition from the heart and lung receptors, the carotid baroreceptors and chemoreceptors were denervated by stripping the common carotid, internal carotid, and occipital arteries. After this procedure, occlusion of the common carotid arteries did not result in an increase in arterial blood pressure. The vagi were cut at the diaphragm.

The response of resistance vessels of both hind limbs and the left kidney to interruption of afferent vagal nerve traffic was studied when only the heart was left in situ (the lungs having been removed) and when only the lungs were left in situ (the heart having been removed). Studies were made during systemic normocapnia and hypercapnia. The details of these preparations have been described previously (15). Ventilation of the extracorporeal oxygenator with 100% O2 maintained the arterial oxygen tension (PaO2) of the experimental dog above 300 mm Hg, the arterial carbon dioxide tension (PaCO2) between 30 and 40 mm Hg, and the pH between 7.30 and 7.40. To produce hypercapnia, the oxygenator was ventilated with 90% O2-10% CO2. In this situation, the PaCO2 remained above 300 mm Hg while the PaO2 increased above 70 mm Hg and the pH decreased below 7.15. Five to ten minutes were required to produce and to reverse these changes.

Comparison of Cardiopulmonary and Carotid Receptors.—The responses of left renal and left hind-limb resistance vessels to withdrawal of inhibitory traffic from the cardiopulmonary region were compared, in closed-chest dogs, with the responses to withdrawal of the inhibitory traffic from the carotid sinuses. The carotid sinuses were vascularly isolated and perfused according to a previously described technique (13, 16) and set at an intrasinus pressure of 220 mm Hg to provide maximal inhibition from these receptor sites (17-19). The intrasinus pressure then was decreased rapidly to 40 mm Hg, at which pressure the carotid baroreceptor inhibition is minimal or absent (17-19). Both vagal nerves then were cold blocked. This sequence was followed because previous studies (13) have shown that the inhibition from the cardiopulmonary receptors is maximally evident in the absence of the inhibition from the carotid mechanoreceptors.

The observations were made during normovolemia and after the firing of receptors in the cardiopulmonary region had been augmented by increasing the blood volume (20, 21). A low-molecular weight dextran solution (isotonic with plasma) at 37°C was infused into a femoral vein over a period of 3 minutes. The increases in blood volume were estimated at 15% and 30%, assuming the total blood volume to be 90 ml/kg body weight (22).

To study the sympathetic nerves to the left hind limb, the left paravertebral sympathetic chain was cut above the level of L4 and the caudal stump was stimulated electrically with 5-msec pulses of supramaximal intensities (> 10 v) and frequencies of 1-14 cycles/sec. To stimulate the sympathetic nerves to the left kidney (23, 24), the left splanchnic nerve was cut at its entrance into the abdomen, and the caudal stump was stimulated electrically as described for the lumbar chain. The delay time of 60 seconds or longer in the perfusion circuit ensured that the measured response was not due to the release of catecholamines from the adrenal glands.

Protocol and Data Analysis.—In the first part of the experiments with only the heart or only the lungs in situ, cold block of the cervical vagal nerves was performed during normocapnia; in the later part, multiple paired vagal blockades were performed during normocapnia and hypercapnia. In the experiments in which inhibition from the cardiopulmonary region and the carotid sinus region was compared, the observations were made in sequence during normovolemia and 15% and 30% hypervolemia. The responses to the various experimental procedures were measured as soon as steady values were obtained. The observations in each dog were summed to obtain the mean ± SE for the group. The statistical significance of the difference in the means was evaluated by Student's t-test. The level of significance was taken as P = 0.05.

Results

Separate Responses of Cardiac and Pulmonary Receptors.—In these experiments, the carotid baroreceptors were denervated 3-4 hours before the observations began. By this time the marked
vasoconstriction of the hind-limb vessels that followed the denervation had disappeared, and blood flow approximated predenervation values.

Cardiac Receptors.—The experiments with only the heart in situ were performed in eight dogs. The cardiac output was $90 \pm 3$ (SE) ml/min kg$^{-1}$ body weight; the left and right atrial pressures were $6.6 \pm 0.3$ and $0.9 \pm 0.2$ mm Hg, respectively. Vagal cold block caused a significant increase in mean aortic blood pressure and significant decreases in hind-limb and renal blood flows (Fig. 1, Table 1). The changes were sustained throughout the period of cold block (2-3 minutes). The mean percent decrease in hind-limb blood flow in the eight dogs was not significantly different from that in kidney blood flow (Table 1).

Pulmonary Receptors.—The experiments with only the lungs in situ were performed in eight dogs in which the input to the aorta was $88 \pm 3$ (SE) ml/min kg$^{-1}$ and the tidal volume was 20 ml/kg; the inspiratory and expiratory pressures were 12.5 $\pm 0.5$ and 2.5 $\pm 0.2$ cm H$_2$O, respectively. Vagal cold block caused a sustained increase in mean aortic blood pressure and sustained decreases in hind-limb and renal blood flows (Fig. 1, Table 1). The mean percent decrease in hind-limb blood flow in the eight dogs was not significantly different from that in renal blood flow (Table 1). The mean decreases in hind-limb and renal blood flows during vagal cold block were not significantly different from those with only the heart in situ.

In all eight dogs with only the lungs in situ, vagal block also was performed with the tidal volume set at 10 and at 40 ml/kg—that is, at half and at twice the control tidal volume. The increase in ventilation from 10 to 40 ml/kg decreased the aortic blood pressure and increased the hind-limb and renal blood flows; with vagal block, similar pressures and flows were recorded at each tidal volume (Fig. 2). Thus, the increase in tidal volume resulted in a greater inhibition of the vasomotor center by the vagal afferents from the lung receptors. The percent decrease from control blood flow in the hind limb during vagal block was not significantly different from the percent decrease in renal blood flow at any of the tidal volumes studied.

Two additional types of observations were made in four of these eight dogs. First, vagal block was performed with the ventilation suspended and the lungs collapsed at atmospheric pressure. In this condition, no response to vagal block was observed in one dog, but the three other dogs showed increases in aortic blood pressure and decreases in hind-limb and renal blood flows that were only slightly less than those observed when the lungs were ventilated with the smallest tidal volume (10 ml/kg). Second, the lungs were removed; this procedure increased the aortic blood pressure and decreased the hind-limb and renal blood flows to values similar to those observed with vagal block before lung removal. In no instance after lung removal did vagal block have any effect on the aortic blood pressure or the hind-limb and renal blood flows.

Hypercapnia.—The data are summarized in Figure 3. In the experiments with only the heart in situ, left and right atrial pressures were not significantly changed by hypercapnia. In the experiments with only the lungs in situ (tidal volume 40 ml/kg), the ventilatory pressures were identical during normocapnia and hypercapnia. In both preparations, hypercapnia caused a significant decrease in base-line aortic blood pressure but did not augment the increase caused by vagal block.

In both experimental preparations, hypercapnia failed to exert a significant effect on the base-line hind-limb blood flow; moreover, it did not significantly modify the decrease in hind-limb blood flow caused by vagal block. In contrast, in both preparations, hypercapnia caused a considerable increase in base-line renal blood flow. With vagal block, the
Table 1

Vascular Responses to Bilateral Cervical Vagal Cold Block with Only the Heart or Only the Lungs In Situ

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<th>Only heart in situ</th>
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<tr>
<td></td>
<td>Initial</td>
<td>Change</td>
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<tr>
<td>Mean aortic blood pressure (mm Hg)</td>
<td>129 ± 12</td>
<td>+25 ± 3</td>
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<tr>
<td>Hind-limb blood flow (ml/min)</td>
<td>104 ± 10</td>
<td>-24 ± 4</td>
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<tr>
<td>Renal blood flow (ml/min)</td>
<td>125 ± 15*</td>
<td>-29 ± 6</td>
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All values are means ± se for observations in eight (in each group) extracorporeally oxygenated, sinoaortic denervated dogs with their vagi divided at the diaphragm and their hind limbs and left kidneys perfused at a constant pressure of 120 mm Hg.

* Equivalent to 3.5 ± 0.4 ml/min g⁻¹ kidney tissue.
† Equivalent to 3.2 ± 0.5 ml/min g⁻¹ kidney tissue.

decrease in renal blood flow was greater during hypercapnia; this response was greater in the heart-only preparation (+162%) than it was in the lungs-only preparation (+38%). The greater response to vagal block during hypercapnia in the heart-only preparation was significant. That the renal vasodilatory response to hypercapnia was dependent on intact vagal afferents was demonstrated by inducing hypercapnia in sequence before, during, and immediately after vagal cold block in six dogs with only the heart in situ (Fig. 4). Before vagal block, renal blood flow was greater during hypercapnia than it was during normocapnia. In contrast, when hypercapnia was induced during vagal block, renal blood flow either did not change or decreased below the normocapnic values. After the vagal block had been ended, the renal blood flow returned to or close to the level seen in the initial hypercapnic state.

To assess the effect of the local increase in arterial PCO₂ on the responses of the kidney and the hind limb, the effects of hypercapnia were compared before and after sympathetic denervation of each area by bilateral splanchnicotomy and by removal of the left lumbar paravertebral sympathetic chain. In both the heart-only (eight dogs) and the lungs-only (six dogs) preparations, hypercapnia increased the blood flow in the sympathectomized kidney to a degree (+41%) similar to that observed before denervation (+33%). In the hind
Effect of hypercapnia on renal blood flow before, during, and after bilateral cervical vagal cold block in six dogs with only their hearts in situ. The kidney was perfused first with hypercapnic blood; then it was perfused with normocapnic blood, and finally the cervical vagi were cold blocked. During the block, the perfusing blood was again made hypercapnic, and then the vagal block was relieved. Renal blood flow is shown as the percent change from the value recorded during normocapnia with the vagi unblocked. Hypercapnia caused an increase in renal blood flow in all dogs with the vagi unblocked but no change (three dogs) or a decrease in flow (three dogs) when the vagi were blocked.

limbs, hypercapnia did not induce a significant increase in blood flow before (+2%) or after (−3%) denervation. The capability of the hind-limb vessels to dilate was shown by the increase in blood flow induced by a close intra-arterial injection of 10 μg of isoproterenol hydrochloride.

Comparison of Carotid and Cardiopulmonary Receptors.—In 13 dogs, withdrawal of inhibitory traffic from the carotid sinus and the cardiopulmonary receptors each resulted in a decrease in kidney and hind-limb blood flows (Fig. 5, left). At all blood volumes, the decrease in renal blood flow caused by vagal block was equal to or greater than that due to the reduction in sinus pressure. In contrast, in the hind limb, the decrease in flow due to vagal block was always substantially less than that resulting from carotid sinus hypotension.

This difference in the reflex control of kidney and hind-limb resistance vessels was more evident from the relative contributions of the carotid and the cardiopulmonary reflexes to the decrease in renal and hind-limb blood flows recorded during interruption of inhibitory traffic from both receptor regions (Fig. 5, right). Combined withdrawal of carotid sinus and cardiopulmonary inhibitory traffic decreased hind-limb blood flow by 88% during normovolemia and by 77% and 83%, respectively, during 15% and 30% hypervolemia. Corresponding decreases in renal blood flow were 42%, 39%, and 40%. Interruption of cardiopulmonary inhibitory traffic was responsible for 17%, 33%, and 32% of the reflexly induced changes in hind-limb blood flow and for 50%, 62%, and 68% of the changes in renal blood flow.

At the end of the experiment, both vagus nerves were cut. A decrease in sinus pressure from 220 to 40 mm Hg caused the same decreases in renal and hind-limb blood flows as those noted with vagal cold block and decreased sinus pressure.

Direct Stimulation of Sympathetic Nerves.—In 12 of the 13 dogs, electrical stimulation of the sympathetic nerves to the hind limb and the kidney was performed after bilateral cervical vagotomy. This stimulation caused an immediate
and sustained decrease in the hind-limb and renal blood flows. With frequencies of stimulation greater than 8 cycles/sec, the percent decreases in hind-limb and renal blood flows were similar (80-90%) (Fig. 6). In contrast, at frequencies less than 6 cycles/sec, the percent decrease in hind-limb blood flow was much greater than that in renal blood flow.

Discussion

Separate Roles of Cardiac and Pulmonary Receptors.—The present study indicates that vagally innervated receptors in the heart and the lungs exert a tonic inhibition on the sympathetic outflow to the hind-limb and kidney resistance vessels. The similar mean decreases in blood flow of 23% and 21%, respectively, when cardiac or pulmonary vagal nerve traffic was interrupted imply a similar role for the heart and the lung receptors in the tonic control of the hind-limb circulation; this situation also applies for the renal circulation (mean flow decreases of 23% and 33%, respectively).

The tonic vasomotor inhibition exerted on both the hind-limb and the kidney resistance vessels by the pulmonary afferents was related to the ventilatory volumes and pressures and was also present during apnea when the lungs were collapsed at atmospheric pressure. These findings are in agreement with the observations of others (8, 9, 25-27) that inflation of the lungs has a reflex depressor influence on the systemic circulation and that this reflex has a low threshold (26). They are difficult to reconcile with the findings of Hainsworth (14), who observed that systemic vasodilation occurred only on hyperinflation; lung inflations at a moderate pressure caused a small vasoconstriction, if anything. Hainsworth (14) suggested that abnormal perfusion of the lungs, as used in other studies, might alter the lung compliance and cause overdilation at smaller inflation pressures. However, this mechanism cannot explain the presence of a tonic vasomotor inhibition during apnea with the lungs collapsed at atmospheric pressure.

During normocapnia there were similar decreases in blood flow to the hind limbs and the kidney (absolute values as well as percents of control) when the vagi were cooled with only the heart and with only the lungs in situ. This finding suggests that neither of these beds is preferentially involved in the tonic inhibition exerted by vagal afferents from the heart or the lungs. It should be pointed out that this conclusion may not apply to all receptors in these regions. For example, in the cat, electrical stimulation of the right cardiac nerve, a procedure that activates afferent fibers that are not normally active, causes greater effects on the renal circulation than it does on the hind-limb circulation (4).

During hypercapnia, the inhibition exerted by cardiac and by pulmonary vagal afferents on the kidney vessels became greater. This finding agrees with those of previous studies in the rabbit in which hypercapnia augmented the vasodepressor reflexes from the aortic arch and the lungs, with a greater effect on the renal bed than on the muscle vascular bed (8, 9). The present study demonstrates that the cardiac reflexes behave in a similar fashion. Thus, it seems that this phenomenon is a general property of reflexes that tonically inhibit the vasomotor center. In the present study, the effect of hypercapnia on the renal circulation was due to an interplay among the local dilator action of CO₂, its excitatory action on the vasomotor center, and a more effective inhibition of this center by the cardiopulmonary receptors. Locally, the increase in CO₂ caused vasodilation, as shown by the experiments with the kidney denervated. This dilation was opposed by the simultaneous excitation of the central neurons so that in the absence of reflex inhibition of the vasomotor center by the cardiopulmonary receptors there was no change or a decrease in renal blood flow with hypercapnia. With the vagi intact, renal blood flow was increased during hypercapnia. Thus, an increase in CO₂ augmented, in an as yet unexplained
way, the inhibition of the vasomotor center normally effected by the vagal afferents; counteracting the central effects of CO$_2$ permitted dilation of the renal vessels.

Regarding possible mechanisms by which the hypercapnia increased the inhibition exerted by the vagal afferents, there was no obvious mechanical cause for increased discharge from the receptors; hypercapnia did not change the ventilatory pressures with only the lungs in situ or the atrial pressures with only the heart in situ. It could be argued that CO$_2$ increases the activity of the cardiopulmonary receptors. However, it is known that CO$_2$ decreases the activity of slowly adapting pulmonary stretch receptors (28), and Coleridge et al. (29) have found that ventilation with CO$_2$ does not increase activity in ventricular fibers characterized by an irregular, sparse discharge. The spontaneous activity of most avian cardiac receptors is negatively correlated with arterial PCO$_2$ (30). Thus, it seems most likely that CO$_2$ acts centrally to accentuate the inhibitory control of the renal vessels by the vagal afferents.

In contrast to the response of the renal resistance vessels, CO$_2$ had little effect on the central vasomotor neurons controlling the hind-limb circulation or locally on the limb resistance vessels. Also, during hypercapnia there was no evidence of an increased inhibition of the central neurons controlling the hind-limb vessels. These differences between the hind limb and the kidney in regard to hypercapnia are still unexplained.

**Roles of Cardiopulmonary and Carotid Receptors.**—Previous studies have shown that the cardiopulmonary receptors exert an inhibition on the vasomotor center that principally serves to oppose the vasoconstriction due to withdrawal of the inhibition exerted by the carotid baroreceptors (13). The present experiments show that this mechanism operates more effectively in the kidney than it does in the hind limb. This difference is partly due to the fact that withdrawal of carotid sinus inhibition with the vagal nerves intact results in such marked vasoconstriction in the hind limb (a reduction in blood flow of 73% compared with 90% during supramaximal direct nerve stimulation) that, of necessity, the vascular response to subsequent interruption of cardiopulmonary inhibition is small. These findings demonstrate the very limited ability of the cardiopulmonary receptors to modify the vasoconstriction in the hind limb due to the withdrawal of carotid inhibition. Withdrawal of carotid sinus inhibition with the vagal nerves intact resulted in a decrease in renal blood flow of 21% or less, but direct renal nerve stimulation reduced blood flow by 88%. However, of the average reduction of 40% in renal blood flow caused by combined withdrawal of carotid and cardiopulmonary vasomotor inhibition, half was due to interruption of cardiopulmonary inhibition during normovolemia; more than 60% was due to interruption of cardiopulmonary inhibition during hypervolemia. These findings are in accord with previous studies which have shown (1) that withdrawal of carotid baroreceptor restraint normally is followed by considerably lower firing rates in renal than in skeletal muscle vasoconstrictor fibers (2, 31) and (2) that for any given reduction in muscle flow resistance the concomitant reduction in renal flow resistance is decidedly more pronounced when the ventricular receptors are stimulated than it is on carotid baroreceptor activation, i.e., the afferent impulse traffic from the ventricular receptors seems to be preferentially oriented toward those central neuron pools that control the vasoconstrictor fiber discharge to the kidney (32).

Although direct supramaximal sympathetic nerve stimulation reduced both renal and hind-limb blood flow by 90%, combined withdrawal of carotid and cardiopulmonary inhibition reduced blood flow in the kidney only by 42% compared with 88% in the hind limb. The stimulus-response curves show that at frequencies less than 6 cycles/sec there was less vasoconstriction in the kidney than there was in the hind limb. The reduced neuroeffector sensitivity of the kidney thus partly explains the lesser vasoconstriction observed in this organ compared with that seen in the hind limb following withdrawal of baroreceptor inhibition.

The experiments provide no explanation for the different shapes of the hind-limb and renal stimulus-response curves. It is possible that the pronounced autoregulation exhibited by the renal vasculature is involved. Kendrick and Matson (33) have suggested that about half of the renal response to carotid occlusion during constant-flow perfusion is due to the local myogenic response to the rise in perfusion pressure and about half to the action of the vasoconstrictor nerves. They did not, however, offer a similar analysis of the response during constant-pressure perfusion. A second point is that the control levels of blood flow in the kidney are near maximal, although those in the hind limb are less than 10% of flows during exercise. Comparison of the response curves to electrical stimulation of the lumbar chain during rest (blood flow 55 ml/min) and simulated exercise (blood flow 257 ml/min) in anesthetized dogs has shown that the

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exercise curve is displaced to the right of the resting curve (34) in a manner similar to the displacement of the renal response curve to the right of the hind-limb curve observed in the present experiments.

The present findings have certain implications regarding the reflex control of renal circulation in abnormal circumstances. For example, during hemorrhage, when the systemic arterial blood pressure and the central venous pressure decrease, input from the carotid and the cardiopulmonary receptors would be diminished, resulting in a strong constriction of the renal and muscle vascular beds. However, in cardiac failure accompanied by a decrease in arterial blood pressure and an increase in central venous pressure, the decrease in carotid sinus pressure would act to constrict the renal vessels, but this change would be opposed by the simultaneous increase in activity of the cardiopulmonary receptors, thus serving to maintain renal blood flow. It has been observed that, in experimental cardiogenic shock, in which left atrial pressure is increased, renal blood flow decreases less than it does in hemorrhagic shock, in which left atrial pressure is decreased (35, 36).

The preservation of renal blood flow during hypercapnia through the mechanism suggested by these experiments would be of obvious benefit in contributing to the restoration of acid-base balance in respiratory acidosis.

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