The Static Limit of Arterial Blood Pressure in the Dog's Hind Limb

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When the femoral artery is occluded in the anesthetized dog, the pressure in the distal segment usually declines progressively and approaches a static limit asymptotically. This static limit is independent of the original degree of vasomotor tone except under extreme conditions. It is concluded that the rapid supervention of reactive hyperemia in the dog vitiates the static limit as an index of vasomotor tone, unless an instantaneous method is developed for its estimation.

In previous studies, it was demonstrated that the curve relating pressure and flow in the maximally dilated hind limb of the dog was virtually linear over a wide range of values. Extrapolation of such curves to zero flow revealed that the pressure axis intercept was progressively augmented when blood of increasing hematocrit ratios was perfused.1,2 Burton has recently emphasized, however, that conclusions based upon such extrapolations are unwarranted, since values were not obtained sufficiently close to zero flow.3

The original purpose of the present study was to ascertain the lower limiting value of arterial pressure when the erythrocyte concentration of the blood was varied. The results tend to confirm Burton's prediction of a constant pressure-axis intercept, independent of the apparent viscosity of the blood. However, in the course of these experiments, it became evident that the vascular reactions of the dog displayed certain fundamental differences from those reported in the rabbit relative to the so-called "critical closing pressure." These discrepancies were investigated in detail.

METHODS

Eighteen experiments were performed on mongrel dogs anesthetized with sodium pentobarbital. Hemodynamic studies were effected on a hind limb after precautions were instituted to preclude collateral circulation. In six of these experiments, this was accomplished by means of a wire cracker; in twelve, the entire leg was severed from the body, connected only by the femoral artery and vein. The cut edges were thoroughly cauterized and in about half of these preparations, a wire tourniquet was placed about the upper thigh to ensure occlusion of any open vessels. After collateral circulation had been obviated by either method, heparin was administered and T-cannulas were inserted into the femoral artery and vein. The rate of pressure decline in the femoral artery was recorded optically by means of Gregg manometers following the temporary application of a clamp proximal to the T-cannula.

RESULTS

Effects of Varying Hematocrit Ratios. In seven experiments, the corpuscular concentration of the circulating blood was altered over a wide range by serial infusions of fresh donor plasma or packed erythrocytes, as previously described.4 The decline in pressure in the femoral artery was recorded at each hematocrit level after complete occlusion proximal to the T-cannula. The pressure drop was registered continually for almost a minute, and then intermittently at one-minute intervals for a total of 10 minutes. The femoral vein also was occluded proximal to its cannula, and the outflow level of the side arm was set at the hydrostatic level of these vessels. In four of these experiments, the femoral arterial clamp was momentarily released until venous outflow was re-established. The clamp was then reapplied, and femoral arterial pressure was again re-
FIG. 1. Graphs showing decline in pressure in distal segment of an occluded femoral artery at different erythrocyte concentrations. Solid circles, changes in pressure during the first ten minutes after occlusion; open circles, pressure drop after a momentary restoration of flow. Hematocrit ratios marked in the upper right hand corner of each graph. Ordinate, pressure in centimeters H₂O; abscissa, time.

The data from a typical experiment are illustrated in figure 1. The solid circles represent the decline in pressure during the first 60 seconds and succeeding nine minutes after occlusion of the femoral artery. The pressure-time curves registered immediately after this 10-minute period of ischemia are represented by the open circles. Pressure is plotted along a logarithmic scale principally to expand the lower pressure values. Although the diagram is arranged as an ascending series of erythrocyte concentrations, the sequence followed in the actual experiment was 59.4, 70.2, 75.5, 50.3, 45.1, and 60.0 per cent.

The figure reveals that at each corpuscular concentration, the pressure declines rapidly at first and then more gradually throughout the period of observation, and appears to approach a limiting value asymptotically. This value has been termed the "static limit" by Gomez. It should be noted that no significant or consistent variation in the static limit is observed over the entire range of hematocrit ratios. The average limiting value is 5.8 cm. H₂O, represented by the horizontal dotted line, and all values lie within ±2 cm. H₂O of this mean level. Furthermore, pressure declines at a greater rate when the limb is relatively more anoxic (open circles), indicating an appreciable lowering of resistance in most cases (notably at hematocrit readings 45.1, 50.3, 50.4, and 70.2). Nevertheless, the limiting value at each corpuscular concentration is virtually identical.

Influence of Vasoconstrictor Drugs. In order to determine whether the static limit is increased or the flow ceases completely at an elevated pressure during vasoconstriction, three types of experiments were performed. In the first, a pressor agent was administered intravenously, and a pressure-time curve was registered from the distal segment of the clamped femoral artery. The data from such an experiment are plotted in figure 2, in which the open circles represent the control conditions. The figure reveals that mean arterial pressure ranges from 138 to 150 mm. Hg. After constriction of the femoral artery, the pressure distally drops steeply at first, and then more gradually, and reaches a minimum value of 3.5 mm. Hg.

Fig. 2. Lower graphs show diminution in pressure in occluded femoral artery before (open circles) and after (closed circles) intravenous administration of 7.5 mg. Wyamine sulfate. Upper graphs depict simultaneous levels of the mean carotid pressure. Ordinate, pressure in millimeters Hg.
four minutes after compression. During the succeeding four minutes, the pressure actually rises approximately 1 mm. Hg. Such a slight rise was observed in only a few other experiments; the most characteristic result was a progressive, though slight, decline which continued for as long as 20 minutes in some studies.

After determination of these control data, 7.5 mg. Wyamine sulfate were administered intravenously; two minutes later the femoral artery was again occluded. The closed circles in figure 2 represent the data obtained immediately afterward. The figure shows that mean arterial pressure is considerably elevated, ranging from 194 to 230 mm. Hg. When the femoral artery was again occluded, the pressure in the distal segment declines much more gradually than during the control period, demonstrating the appreciable increase in resistance, probably due to vasoconstriction. Nevertheless, the pressure never stabilizes at any fixed value, but diminishes progressively and finally attains a value slightly below the control limit.

Because it was strongly suspected that the superimposition of reactive hyperemia is an important factor in masking a maintained critical closing pressure, a second technic was devised. A vertical glass column was attached to the side-arm of the femoral arterial cannula, and this cylinder was filled to varying levels with the animal's arterial blood. The rate of pressure decline was initiated at progressively lower levels, and the duration of each observation was limited to one minute or less. An extremely sensitive membrane was employed on the optical manometer to permit pressure measurements to be made with an accuracy of ±0.1 mm. Hg. Normal circulation was established through the extremity for about two minutes between each brief pressure-time registration.

A representative experiment of this design is illustrated in figure 3. On the left-hand side of the figure, the rate of pressure decline is plotted for initial pressures of 60, 27, and 16 mm. Hg, respectively. During the 30- to 35-second periods of observation, the pressure declines progressively and rather steeply. Privine hydrochloride (2 mg.) was then administered intravenously. The control mean arterial pressure of 125 to 128 mm. Hg was elevated to a range of 157 to 167 mm. Hg when the data represented by the pressure-time curves depicted on the right-hand side of the figure were obtained. Seven pressure-time curves were registered, beginning at initial pressures of from 82 to 15.3 mm. Hg. The figure reveals that in all cases the rate of pressure drop is markedly diminished, indicating a severe degree of vasoconstriction in comparison with the control state. At initial pressures of 40 mm. Hg and below, the slight rise in pressure during the first few seconds of observation is indicative of some regurgitation of blood from the limb to the column immediately after occlusion of the proximal segment of the artery. After the first several seconds, however, a slight but progressive diminution in pressure is manifest in all curves except the lowest. In the...
In a third type of experimental approach, a massive dose of a vasoconstrictor material was introduced intra-arterially in an attempt to demonstrate a maintained, complete cessation of flow at an elevated pressure. The results of a representative experiment are depicted in figure 4. In this experiment, 5 mg. of Privine hydrochloride were mixed with 50 cc. of the dog's arterial blood, and introduced into a vertical cylinder attached to the side arm of the femoral arterial cannula. The initial rapid pressure drop evident in the figure represents the time required for the Privine to traverse the connecting rubber tubing and larger arteries. The pressure drop is arrested at 87 mm. Hg, and is followed by a slow rise until a plateau develops at 90 to 91 mm. Hg. After approximately 100 seconds, however, the pressure again falls, and a definite decline is evident for the remainder of the observation period, even though the blood entering the limb now contains Privine in high concentration.

**Influence of Elevated Venous Pressure.** Escape of blood from the perfused limb could account for the absence of a stable critical closing pressure in most of our experiments. In order to rule out this possibility, the hydrostatic level of the venous outflow tubing was varied stepwise in three experiments. If a significant leak were present, arterial pressure would approach the zero reference level of the artery rather than the venous outflow level.

Data from a representative experiment are presented in figure 5. The closed circles represent the decline in femoral arterial pressure distal to the point of constriction when the venous outflow tubing is adjusted to the same hydrostatic level as the femoral artery. Arterial pressure attains a value of 9.5 cm. H$_2$O 10 minutes after occlusion. An identical value obtains at the end of an equal period of time when venous pressure is elevated to 5 cm. H$_2$O (open circles). Raising venous pressure to 10 cm. H$_2$O results in a terminal arterial pressure of 10.5 cm. H$_2$O (open squares). Further augmentation of venous pressure to 15 cm. H$_2$O causes arterial pressure to stabilize at an equal value (closed squares). When the venous pressure is elevated to 20 cm. H$_2$O, the arterial pressure attains a slightly lower value, namely 19.3 cm. H$_2$O.
However, it was noted that the level of blood in the venous outflow tube had also receded slightly toward the end of this period of ischemia. The results of similar experiments were identical. Therefore, escape of blood from the vascular system could not have occurred at a sufficiently rapid rate to account for the progressive fall in arterial pressure in most of our experiments.

**Discussion**

On the basis of the first series of experiments, it appears that the minimum pressure necessary to initiate flow is independent of the anomalous rheologic properties of the blood. In all experiments similar to that depicted in figure 1, the limiting pressure approached in the distal segment of the occluded femoral artery was not modified appreciably when the hematocrit ratio was varied over a wide range of values. This constant static limit prevailed even when the vascular bed was maximally dilated. It had been reported previously that the pressure-axis intercept is identical for the pressure-flow curves of blood and electrolyte solutions in perfused, isolated vascular beds. Therefore, the concept that blood is a plastic fluid requiring an appreciable shearing force to initiate flow is not tenable. This is substantiated further by the experiments in which the venous outflow pressure was elevated by stages (figure 5). At the higher levels of venous pressure, arterial pressure approached an identical value. If blood were a true plastic fluid, flow would cease when the arteriovenous pressure difference equalled the "yield pressure."

Rather, the static limit of the arterial pressure must depend upon the physical nature of the vascular bed itself and its supporting structures. A comprehensive, critical analysis of the forces operating on the blood vessels has been expounded recently by Burton. On the basis of Laplace's law, Burton postulated that blood vessels would collapse completely under certain critical conditions. Flow would then cease, despite an appreciable difference in pressure between the arterial and venous segments. He argued further that this "critical closing pressure" varied concordantly with the degree of vasomotor tone. Subsequent experimental work on the rabbit and man has served to support these views.

In most of the experiments on the dog described herein, a stable critical closing pressure was not detected. Instead, the pressure continued to decline with time at a progressively diminishing rate, and approached a static limit asymptotically. Furthermore, the static limit did not vary with vasomotor tone except under the most extreme conditions. Thus, the static limit was uninfluenced by vasodilatation (fig. 1) or by degrees of constriction which might be encountered under physiologic conditions (fig. 2). Only when massive doses of constrictor agents were administered intra-arterially was a complete cessation of flow manifested, and then it was maintained for scarcely more than a minute (fig. 4).

It has been reported that, using similar techniques, complete closure of the vascular bed in rabbits is maintained for longer than 15 minutes, even with far more moderate degrees of vasoconstriction. The reasons for the divergent results in rabbits and dogs are uncertain. In studies in which flow is rapidly and appreciably diminished a significant degree of vasodilatation develops within a few seconds after the onset of ischemia in the dog. The progressive phase of dilatation is undoubtedly the vascular response to tissue anoxia and the accumulation of metabolites. Instantaneous vasomotor changes, however, may result from the rapid decrease in intravascular pressure occasioned by constriction of the femoral artery. It has been demonstrated that, even in a denervated vascular bed, a sudden variation in pressure elicits an immediate compensatory vasomotor reaction.

Therefore, when an attempt is made to ascertain the static limit of arterial pressure by observing the decline in pressure in the distal segment of the femoral artery or in a vertical column connected to the artery, the vascular bed dilates rapidly and progressively. In figure 1, the steeper descent in the second curve (open circles) at each hematocrit level is cogent evidence of an appreciable reduction in vascular resistance by the end of a 10-minute observation period. Thus, during a determination of the limiting value of arterial pressure, the
vasomotor tone must have been diminishing as the static limit was being approached. Since a maximum degree of dilatation is virtually attained after 10 minutes of ischemia, the vasomotor tone at the end of each pair of pressure-time curves was identical, although the vascular resistance was considerably different during the first several seconds of each registration. Williams and Schroeder also observed a progressive decline in pressure following the sudden occlusion of a major artery in dogs, although the periods of observation were of shorter duration. They also observed that ischemia persisting for two minutes or less resulted in marked vasodilatation.

If the static limit is actually dependent upon the degree of vasomotor tone, as Burton avers, then an instantaneous method for measuring the critical closing pressure must be contrived. The experiment represented in figure 3 illustrates an attempt to approximate this criterion. Unquestionably, the rate of pressure drop is considerably less after Privine is given. A slight but detectable decline in pressure is evident in all but the lowest curve after administration of this vasoconstrictor material. However, the interpretation of these results is restricted by the degree of accuracy of the experimental techniques employed. If a conventional mercury manometer were employed, for example, then the pressure-time curve beginning at 26.0 mm. Hg would appear constant, since the maximum change during the one-minute observation period was only 0.6 mm. Hg. It is very probable that the lowest pressure-time curve would also show a progressive pressure diminution with time if a method accurate to ±0.01 mm. Hg were employed, rather than the ±0.1 mm. Hg accuracy attained in this experiment. Comparison of the time rates of change of pressure before and after Privine affords a much more convincing demonstration of the degree of vasoconstriction than does an attempt to estimate the static limit of such curves. Therefore, unless a virtually instantaneous method is developed for determining critical closing pressure, analysis of the pressure-flow curves, as recommended by Green and his colleagues, remains the most valid technique for evaluating changes in vasomotor tone in the dog.

SUMMARY

The decay of pressure was recorded optically in the distal segment of the occluded femoral artery of the dog under a variety of experimental conditions. In most cases, the pressure declined progressively during the entire observation period (maximum, 20 minutes), and approached a static limit asymptotically. In any given experiment, this static limit was independent of the apparent viscosity of the blood and of the degree of vasomotor tone. Only when a massive dose of a vasoconstrictor drug was administered intra-arterially did flow cease entirely at a significantly elevated pressure. Even under these conditions, arterial inflow was halted for little more than one minute, after which the pressure declined progressively throughout the remainder of the period of observation.

The diminution in flow coincident with the decline in pressure during each pressure-time recording undoubtedly resulted in tissue ischemia. The consequent supervention of reactive hyperemia is probably the major factor responsible for the failure to detect a stable critical closing pressure even when a pressor agent was administered systemically. Therefore, comparison of pressure-flow curves is probably a more valid method for assessing vasomotor tone in the dog.

REFERENCES


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