Pressures in Cat Mesenteric Arterioles and Capillaries during Changes in Systemic Arterial Blood Pressure

By Robert W. Gore

ABSTRACT
An interpretive model of the myogenic autoregulatory response of cat mesenteric arterioles has appeared in the literature; it describes arteriolar dimensional changes during changes in mean systemic arterial blood pressure in terms of tension-radius diagrams (Laplace relationship). The original model assumes that arteriolar pressure is a simple, linear function of systemic blood pressure and that arteriolar pressure is always 40% of systemic blood pressure. The purpose of the present study was to test the validity of these assumptions. Using the isolated, autoperfused mesentery of 14 cats, direct, simultaneous measurements of diameter and pressure were made in microvessels during changes in systemic blood pressure. Diameters and micropressures were recorded with a video filar micrometer system and a servonull transducer, respectively. Control microvascular pressure, dimensional distributions, and stress distributions were established when systemic blood pressure was set at 100 ± 10 (SD) mm Hg. Three regions of the arteriolar vasculature were defined and identified for study in terms of these control states. Pressures in the arteriolar regions were a linear function of systemic blood pressure, thus confirming the validity of the previous assumption. Capillary pressures tended not to follow this pattern; pressure in five of eight capillaries sampled was relatively independent of changes in systemic blood pressure between 100 and 40 mm Hg. The apparent constancy of capillary pressure during changes in systemic blood pressure was examined in terms of the modular arrangement of mesenteric microvessels and resistance changes, and the question of physiological regulation of capillary pressure was considered. Data are presented to suggest that a constant capillary pressure in mesentery during changes in systemic blood pressure is primarily the consequence of the vascular geometry peculiar to this tissue.

KEY WORDS microcirculation autoregulation tangential stress radius-wall thickness ratios pressure regulation stress-strain relationship postcapillary-precapillary resistance ratios

Johnson (1) investigated the autoregulatory activity of single arterioles in isolated, autoperfused cat mesentery. He directly measured changes in the diameter of arterioles when mean systemic arterial blood pressure was changed. Following single step reductions in arterial blood pressure, 70% of the arterioles sampled showed a biphasic change in diameter indicative of a myogenic autoregulatory response. Half of these autoregulating arterioles also showed an inverse relationship between steady-state diameter and systemic blood pressure, indicating that the response was active. Johnson then developed an interpretive model of the myogenic autoregulatory response from these data by analyzing the results in terms of the Laplace relationship which equates vessel wall tension with the product of transmural pressure and vessel radius. He measured arteriolar diameters directly in the microvasculature; however, he did not record the corresponding arteriolar pressures. Therefore, to calculate vessel wall tension and construct tension-radius diagrams for individual arterioles, Johnson estimated values of arteriolar pressure at the sites of the dimensional changes. He assumed that arteriolar pressure was 40% of systemic blood pressure and that this pressure fraction (40%) remained constant relative to systemic blood pressure changes. In other words, he regarded arteriolar pressure as a simple, linear function of systemic blood pressure. The absolute value of the pressure fraction was not crucial to the analysis of the myogenic response set forth in Johnson’s paper (1). However, the conclusions drawn from the analysis did depend on the validity of the assumption that arteriolar pressure was always a constant fraction of systemic blood pressure. Richardson and Zweifach (2) measured microvascular pressures in cat mesentery, but their...
studies did not include a systematic examination of arteriolar pressure as a function of changes in systemic blood pressure. Stomberg and Fox (3) observed a straight-line relationship between pial arterial pressure and systemic blood pressure in the cat; this finding tends to validate Johnson's (1) assumption. However, it is difficult to apply the results of observations recorded from small arteries on the surface of the brain to conditions within arterioles in the mesentery. Johnson's (1) observations provide a semiquantitative means of conceptualizing the myogenic autoregulatory response on the surface of the brain to conditions within arterioles in the mesentery. Johnson's (1) observations provide a semiquantitative means of conceptualizing the myogenic autoregulatory response and raise serious questions about the validity of the theory of critical closure (4). Therefore, it is important to test the assumption on which his analysis is based. The following experiments were designed for that purpose.

Methods

Experimental Preparation

Experiments were performed on the isolated, autoperfused mesentery of 14 cats (2-3 kg). The cats were given propiomazine hydrochloride (0.11 mg/kg, i.m.) and anesthetized with a 10% solution of alphachloralose in Carbowax-200 (75 mg/kg, iv). A loop of ileum with attached mesentery was then surgically isolated; details of this procedure have been described previously (5).

The isolated segment was mounted under a Leitz microscope on a specially constructed Lucite stage (5). The surface of the mesentery was suffused with Tris-buffered physiological solution (37 ± 1°C, pH 7.4 ± 0.2), and the suffusate was drained from the stage through a vacuum line. Temperature was monitored with a thermistor probe located under the mesentery and controlled by circulating water from a constant-temperature bath through a jacket in the stage. The preparation was autoperfused from the femoral artery, and blood was returned via a reservoir to the cat's jugular vein. Venous outflow and arterial perfusion pressures were monitored through side branches in the perfusion lines. The surface of the mesentery was adjusted to the appropriate height above the mesentery. Arterial perfusion pressure (systemic blood pressure) to the mesentery could be adjusted with a Caskell clamp on the arterial line of the preparation. The pressure pipettes (tip 1-3μ, o.d.) were inserted sharpened pressure pipettes through the arterioles and capillaries, and into the microcirculation. These experiments established the control and reference conditions against which all subsequent experiments were compared. The data were obtained by making direct measurements of pressure and diameter at different points along the vascular tree from the smallest arteries, through the arterioles and capillaries, and into the venous outflow while the pipette tips were in the suffusion solution just outside the vessels. All penetrations were made at right angles to the direction of blood flow. Microvascular pressures, large artery and vein pressures, and total blood flow were all recorded on an Offner type R chart recorder. Sensitivity ranges of 10, 20, and 40 mm Hg/cm were used, and the total system accuracy was ±0.5, ±1, and ±2 mm Hg, respectively. Vessel dimensions were measured with a video filar micrometer. Microvessels were monitored through the microscope with a television camera (modified Sony DXC-2000A), and a permanent record was obtained on video tape (Sony Videocorder AV-3650). During an experiment, the image was viewed either directly through the microscope or on a television monitor (Sony model CVM-110U). Time references were recorded on the audio track of the video tape and on the chart recorder so that events which occurred in the video record could later be referred to the correct time sequence in the pressure and flow records. The video recording was played back through an X-Y indicator (ITP model 128A reference line generator) which displayed two horizontal and two vertical reference lines on the video monitor. The positions of these line pairs on the monitor could be adjusted with potentiometers on the front of the X-Y indicator. The potentiometers were precalibrated for each magnification against the image of a stage micrometer. The appropriate pair of lines was superimposed over the image of a vessel at the boundaries of the internal and the external wall, and vessel dimensions were read from the potentiometers. This system could also be used during an experiment by simply interposing the X-Y indicator between the television camera and the monitor.

Generally, two optical magnifications were used. At the highest magnification, 100μ was equivalent to 11 cm on the monitor (50x objective, 8x eyepiece, plus camera lens); the total magnification was therefore 1,100x. A 32x objective was used in experiments requiring a larger field of view. In this case, 156μ was equivalent to 11 cm on the monitor so that the total magnification was 704x. At 1,100x the estimated accuracy of the video filar micrometer was ±1μ and the precision was ±0.6μ. At 704x the estimated accuracy was ±1.5μ and the precision was ±1μ. As an added precaution to ensure that the video system was properly calibrated, periodic measurements were made with a Vickers image-shearing eyepiece and compared with the results obtained with the video filar system.

Results

An initial series of experiments was performed to determine the pressure, dimensional, and stress distributions normally existing in the cat mesenteric microcirculation. These experiments established the control and reference conditions against which all subsequent experiments were compared. The data were obtained by making direct measurements of pressure and diameter at different points along the vascular tree from the smallest arteries, through the arterioles and capillaries, and into the...
Microvascular pressures in cat mesentery

Venous outflow pressure was adjusted to 7 ± 0.5 mm Hg. Total segmental flow averaged 25 ± 8 ml/min 100 g⁻¹.

Control distribution of transmural pressure

Figure 1 summarizes 180 measurements from a total of 85 vessels in ten cats and shows the distribution of pressure as a function of mean vessel diameter (D) across the microcirculation from the smallest arteries (D = 120 ± 10 [μm]) to the venules (D = 78 ± 5 [μm]) when systemic arterial blood pressure was 100 mm Hg. The numbers above each point refer to the number of trial measurements. An average of two trial measurements (penetrations) was made in each vessel sampled. The pressure distribution (Fig. 1) is comparable to that observed by Richardson and Zweifach (2) and Zweifach (11). The major pressure drop occurred in arterioles with mean diameters between 35 and 45 μm. The internal diameters of these vessels ranged from 31 to 41 μm. Richardson and Zweifach (2) found that the major pressure drop in their preparations was confined to slightly smaller arterioles with internal diameters between 25 and 30 μm. The slight difference in the apparent location of the major pressure drop in these two studies can be explained by differences in mean systemic arterial blood pressure. The mean systemic blood pressure in the preparations of Richardson and Zweifach averaged 94 ± 23 (SD) mm Hg—6 mm Hg less than that in the present experiment. Therefore, the internal diameters of vessels at comparable levels in the microvasculature should have been slightly smaller in their study (2). However, comparison of Figure 1 with the most recent data reported by Zweifach (11) indicates that the difference can also reflect differences in the magnitude of vascular tone within the preparations used in the two laboratories.

In Figure 1, the average pressure at the arterial input to the capillaries (D = 12 ± 4 [μm]) was 32 ± 3 (SD) mm Hg; it decreased to 28 ± 4 mm Hg in the smallest venules (D = 20 ± 3 [μm]). Further downstream in the largest venules sampled (D = 78 ± 5 [μm]), pressure was 23 ± 2 mm Hg. The rather high absolute pressure and the flat pressure profile in the capillaries and venules is consistent with the observations of Zweifach and Intaglietta (12) which indicate that fluid filtration occurs along the entire length of the capillaries in mesentery and omentum. In his latest studies, Zweifach (11) observed a larger pressure difference across the capillaries (8–14 mm Hg), but the high absolute capillary pressure in the mesentery (30–40 mm Hg) was further confirmed.

Control distribution of vessel dimensions

The corresponding dimensions of the 85 vessels in which transmural pressures were recorded were expressed as the ratio of internal radius to wall thickness (r/8) and are shown in Figure 2 plotted as a function of mean diameter. The ratio decreased in magnitude on the arterial side from 6.5 ± 0.7 (SD) in 120 μm small arteries to 2.5 ± 0.7 in 12 μm arterial capillaries and then increased again on the postcapillary side.

Control distribution of stress

Previous experiments on frog mesenteric microvessels (13) have demonstrated that the response of vessels to norepinephrine is determined in part by their initial stress state and that the vessels respond maximally only if their initial stress is within an "optimum range" of 1–1.5 × 10⁵ dynes/cm². Presumably, the initial stress state of vessels is also an important determinant of their responsiveness to mechanical and electrical stimuli as well as to chemical agents. These earlier experi-
merits (13) established the importance of defining the initial stress conditions within each preparation studied so that meaningful comparisons among different vessel types could be made. For this reason, the average tangential stress distribution within the cat mesenteric vessels was calculated from the measured values of mean pressure (Fig. 1) and $r/\delta$ (Fig. 2). The results shown in Figure 3 define the average stress present at any point along the vasculature between small arteries and venules when systemic blood pressure is 100 ± 10 mm Hg. These data represent the normal operating stress state of the cat mesenteric microvessels and are the control conditions against which all subsequent experiments were referenced. Interestingly, the control stress in terminal arterioles was between $1 \times 10^5$ and $2 \times 10^5$ dynes/cm², which is essentially the same range previously recorded for control and optimum stress in frog mesenteric arterioles (13).

RELATIONSHIP BETWEEN MICROVASCULAR AND SYSTEMIC ARTERIAL BLOOD PRESSURE IN THREE ARTERIOLAR SEGMENTS

Four cats were used to study the relationship between microvascular and systemic arterial blood pressure changes. Cats were prepared as described previously, and mean systemic blood pressure was adjusted to 100 mm Hg so that the pressure and dimensional distributions throughout the microcirculation approximately matched the previously defined control conditions (Figs. 1–3). A servo-pressure pipette was inserted into a large arteriole which was selected so that its mean diameter measured approximately 60–70µ. Transmural pressure and vessel dimensions were recorded, and wall stress was calculated. The observed values were compared with the control pressure and stress distribution curves (Figs. 1 and 3) to identify the correct location of the large arteriole on the control curves and to ensure that the control conditions had, in fact, been established within the vessel. Systemic blood pressure was then raised and lowered in steps of approximately 10–20 mm Hg by adjusting the Caskell clamp on the arterial perfusion cannula, and the corresponding micropressures and dimensions were recorded. When sufficient data were obtained, pressure was returned to the control level, and the pressure pipette was removed. This procedure was then repeated in arterioles further downstream. Finally, pressures were recorded in capillaries.

Since the initial conditions of each arteriole sampled were always compared and adjusted to the same control stress state, it was possible to quantitatively define three distinct arteriolar segments which were consistently and repeatedly identifiable within and among the tissue preparations. The data from all the mesenteries studied could therefore be combined and compared in a
meaningful fashion. A total of 17 arterioles was sampled. The results, expressed in terms of wall stress, are shown in Figure 4; the three arteriolar segments studied are identified. The data are superimposed on the control stress distribution curve (solid line, same as curve in Fig. 3 for vessels between 12 and 70μ). The three stress-diameter curves (broken lines) are best-fit lines through the data for terminal arterioles (27μ), arterioles (45μ), and large arterioles (63μ). The open circles are the stress states of each vessel sampled when systemic blood pressure was initially adjusted to 100 mm Hg. They represent the normal operating state of these three segments of the arteriolar vasculature when systemic blood pressure is normal. The solid circles are the stress-diameter states which resulted when systemic blood pressure was varied in steps above and below 100 mm Hg. The means and SD of the control parameters (average for open circles) for the four terminal arterioles were mean pressure (P) = 39 ± 5 mm Hg, mean diameter (D) = 27 ± 1μ, r/δ = 3.7 ± 0.2, and stress (S) = 1.9 x 10^5 ± 0.1 x 10^5 dynes/cm². The averages for the five arterioles were P = 58 ± 7 mm Hg, D = 45 ± 2μ, r/δ = 4.9 ± 0.3, and S = 3.8 x 10^5 ± 2 x 10^5 dynes/cm². The averages for the eight large arterioles sampled were P = 74 ± 4 mm Hg, D = 63 ± 1μ, r/δ = 5.0 ± 0.2, and S = 5.0 x 10^5 ± 0.3 x 10^5 dynes/cm².

The relationship between microvascular and systemic blood pressure was examined by plotting the pressures recorded from these arteriolar segments as a function of systemic arterial blood pressure. The results from the 63μ large arterioles, 45μ arterioles, and 27μ terminal arterioles are shown in Figure 5. The open circles are the control pressures in each of the vessels sampled and correspond to the control states in Figure 4. The equations for a least-squares fit for the three arteriolar segments are

\[ P_{63} = (0.83 ± 0.02)P_a - 4.24 ± 1.65, \]

\[ P_{45} = (0.58 ± 0.03)P_a + 3.05 ± 2.77, \]

\[ P_{27} = (0.39 ± 0.03)P_a + 1.48 ± 2.30, \]

where \( P_{63}, P_{45}, \) and \( P_{27} \) represent the arteriolar pressure in 63μ large arterioles, 45μ arterioles, and 27μ terminal arterioles, respectively, and \( P_a \) denotes mean systemic arterial blood pressure. The errors are SE. The slopes of the regression lines for each individual vessel within a given arteriolar category were not significantly different from one another so that the data for each arteriolar type could be represented by a single regression line as shown. However, the slopes of the regression lines among the three arteriolar categories were significantly different (5% level) so that the results do, in fact, represent three distinct data populations.

Since venous pressure was held constant at 7 mm Hg, arteriolar pressures in the mesentery should have approached 7 mm Hg when mean systemic arterial blood pressure was reduced to 7 mm Hg. The data from the 27μ and 45μ arterioles extrapolate to \( P_{27} = 4.2 ± 2.1 \) (SE) mm Hg and \( P_{45} = 7.1 ± 2.6 \) mm Hg, respectively, at \( P_a = 7 \) mm Hg and are not statistically different from 7 mm Hg. However, the data from the 63μ large arterioles extrapolate to \( P_{63} = 1.6 ± 1.5 \) mm Hg at \( P_a = 7 \) mm Hg, which is statistically different from 7 mm Hg. The last 5 data points (Fig. 5, 63μ vessels) at \( P_a < 20 \) mm Hg seem low and do not follow the trend predicted by the other 54 data points. The fact that \( P_{63} \) is significantly different from 7 mm Hg at \( P_a = 7 \) mm Hg could be explained if the last 5 data points were in error by only 3 mm Hg. Indeed, 4 of the last 5 data points were measured in the same vessel and therefore have a common feature. It is possible that a small plasma leak developed around the pipette while recordings were being taken from the vessel.
in question. This phenomenon could account for the rather low values represented by the last 4 data points.

**RELATIONSHIP BETWEEN CAPILLARY PRESSURE AND SYSTEMIC ARTERIAL BLOOD PRESSURE**

Pressures were recorded in a total of eight capillaries in four cats. The results are shown in Figure 5 (bottom right); the open symbols again represent the control parameters for each vessel sampled. When systemic blood pressure was set at 100 ± 10 mm Hg, the mean of the control capillary pressures (average of open symbols) was 30 ± 3 (SD) mm Hg and the mean capillary diameter was 10 ± 3 µ (SD). The equation for a least-squares fit through all of the data points (curve C) is

\[ P_{c} = (0.14 ± 0.03)P_{a} + 17.00 ± 2.01, \]

where \( P_{c} \) represents mean capillary pressure, the superscript denotes curve C, and the errors are SE.

Pressures in three of the capillaries (Fig. 5 bottom right, triangles) showed a direct, linear relationship to changes in systemic arterial blood pressure consistent with the results from arterioles. More interesting, however, were the results recorded in the other five capillaries (Fig. 5 bottom right, circles). Capillary pressure in these vessels was relatively constant over a wide range of systemic blood pressures. In some cases, capillary pressure actually increased as systemic blood pressure was decreased in the range 110 to 65 mm Hg.

Johnson and Wayland (14) and Richardson and Johnson (15) measured red cell velocities in individual capillaries in the mesentery and found that capillaries could be separated into different groups according to their velocity patterns. In like manner, the capillary pressures in Figure 5 appear to fall into different categories. The data were further analyzed to see if this supposition was statistically justified.

An analysis of covariance was performed to test the hypothesis that the slopes of the regression lines for the individual capillaries were equal. The slopes for five of the capillaries were not significantly different from one another (5% level), indicating that these capillaries were from the same population. Therefore, the data could be combined and fitted with a single regression line. The equation for a least-squares fit through these data (Fig. 5 bottom right, curve A) is

\[ P_{c} = (0.04 ± 0.05)P_{a} + 28.34 ± 4.34. \]

The slopes for the remaining three capillaries were also not significantly different from one another but

**FIGURE 5**

Micropressures measured in the three types of arterioles defined in Figure 4 and in capillaries expressed as a function of mean systemic arterial blood pressure. Open symbols are control pressures when systemic blood pressure was 100 ± 10 mm Hg. They also correspond to the control conditions in Figure 4. See text for details on capillary data.
MICROVASCULAR PRESSURES IN CAT MESENTERY

were significantly greater than the slopes for the other five capillaries. It could be concluded, therefore, that the results from three of the capillaries were from a different data population and could justifiably be combined and fitted with a separate regression line. The equation for a least-squares fit through these data (Fig. 5 bottom right, curve B) is

\[ P_r = (0.30 \pm 0.03)P_t - 0.83 \pm 2.58. \]

Although the sample size was very small, this analysis suggests that there were two different sample populations of capillaries. Furthermore, the analysis of covariance reveals that the results from all eight capillaries cannot be statistically combined and fitted with a single regression line so that curve C, in fact, is an invalid representation of the data.

Discussion

The original purpose of this paper was to measure microvascular pressures in the isolated, autoperfused cat mesentery to verify whether arteriolar pressure is a simple, linear function of perfusion pressure. It is obvious from the results in Figure 5 that pressure throughout the length of the arteriolar tree was a linear function of systemic blood pressure, as Johnson (1) earlier assumed. Furthermore, the average pressure in terminal arterioles (D = 27μ) was 39 ± 5 mm Hg when systemic blood pressure was normal. In other words, terminal arteriolar pressure was essentially 40% of systemic arterial blood pressure. This pressure is almost exactly that assumed and predicted by Johnson (1) for vessels of this size. More importantly, the pressure fraction remained constant for all three arteriolar segments. That is, when systemic blood pressure was reduced by, say 20% from 100 to 80 mm Hg, pressure in all three arteriolar segments also decreased by 20% so that pressure in the large arterioles decreased from 74 to 59.2 mm Hg, pressure in arterioles decreased from 58 to 46.4 mm Hg, and pressure in terminal arterioles decreased from 39 to 31.2 mm Hg. It may be concluded, therefore, that the assumption on which Johnson (1) predicated his analysis and description of the myogenic response of single arterioles is valid and that the tension-radius diagrams which he constructed to explain his results are not only qualitatively but also quantitatively correct.

Johnson (1) examined the response of a total of 34 arterioles to reductions in systemic arterial blood pressure. Vessels were classified as autoregulating if they showed a transient or a biphasic change in diameter following a step change in pressure. Of the 24 vessels which autoregulated, 12 increased their steady-state diameter and the remaining 12 either decreased or did not change their steady-state diameter. The average increase in diameter following a 50% reduction in systemic blood pressure (ref. 1, Table 1) for all 24 autoregulating vessels was only 1.7 ± 2.5μ (SD). In the present study, 5 of the 17 arterioles sampled also showed a transient change in diameter and therefore autoregulated according to Johnson's (1) interpretation. Two of the vessels were in the 63μ category and 3 were in the 45μ category. None of the 27μ vessels sampled appeared to autoregulate. The steady-state diameters of the 5 vessels which appeared to autoregulate following pressure reduction were 2–4μ greater than the control diameters. Though the degree of dilation was small, it was consistent with Johnson's (1) observations. However, the transient change and the subsequent dilation occurred only when systemic blood pressure was first raised above control (100 mm Hg) to between 110 and 120 mm Hg and then suddenly lowered to about 60 mm Hg. It must be emphasized that, if large diameter increases occur following pressure reduction, then the relationship between arteriolar and systemic blood pressure would be nonlinear. In this case, if arteriolar pressure is not actually measured, then one cannot predict arteriolar pressures by simply multiplying systemic blood pressure by some constant fraction, and an analysis such as Johnson used would be incorrect. However, this situation does not seem to occur in the cat mesentery, since the steady-state diameter changes in autoregulating vessels are very small in this tissue.

Pressures in three of eight capillaries sampled were also a linear function of systemic blood pressure and consistent with the arteriolar pressure data. However, a more intriguing result was the observation that pressure in five of eight capillaries sampled remained relatively constant in proportion to large changes in systemic blood pressure. These results raise the question whether hydrostatic pressure may be regulated in a certain fraction of the capillaries. Indeed, Zweifach (16) recorded similar results and suggested that capillary pressure, in addition to flow, may be subject to some form of physiological control.

In attempt to explain the observations in Figure 5 (bottom right, curve A), it is interesting to speculate whether direct control and maintenance of a
constant capillary pressure would be a useful mechanism. Under normal physiological conditions, it would seem reasonable for capillary pressure, and therefore blood-tissue fluid balance, to be maintained. However, in conditions which result in a decrease in total blood volume, fluid reabsorption would be the "desired" response; regulation of a constant capillary pressure would then actually be detrimental, particularly in the case of mesenteric capillaries which have been shown to be primarily a filtration network (12). Although this argument is purely teleological, it is sufficient reason to question the existence of a direct, active physiological control of capillary pressure. The observation that pressure in a certain fraction of capillaries remains relatively constant during large changes in systemic blood pressure may only be a secondary reflection of other mechanisms associated with flow regulation or merely the consequence of the architectural arrangement of the mesenteric vasculature. For the moment, three possible explanations may be suggested to account for the results shown in Figure 5 (bottom right, curve A). The results may be an artifact introduced by nature of the servopressure technique, they may be due to a passive or an active adjustment in the postcapillary-precapillary resistance ratio, or they may reflect a redistribution of flow in the microvasculature as a consequence of the architecture of the mesenteric vasculature.

Consider the first possibility. The servonull pressure transducer is basically an impedance-measuring device, and proper operation of the system requires that the pipette tip be open and unobstructed. If the pipette tip becomes partially obstructed during the course of a measurement, the frequency response of the system may be reduced. In this case the system still records a steady pressure but may be substantially less sensitive to pressure changes. This situation arises when the pipette does not completely penetrate the vessel wall or when it is inserted through the vessel and touches the inside of the opposite wall. These problems occur most frequently when measurements are taken from very small vessels in which it is more difficult to discern the exact location of the pipette tip in the vessel lumen. They are always a potential source of error in measurements of capillary pressures. However, a pulse pressure of 1-3 mm Hg, synchronous with the heart rate, was measured in all capillaries considered in this paper. The frequency response was therefore not measurably altered during penetration of the vessels. After the vessels were penetrated but before systemic blood pressure was lowered, a small quantity of fluid was ejected from the pipette to see if the tip was patent and to identify the location of the tip in the lumen. Finally, the microscope image was recorded at high magnification on video tape for the duration of each experiment and was later reexamined to ensure that the pipettes were properly inserted. Therefore, it is unlikely that the data for curve A are merely an artifact, but this possibility cannot be completely ruled out.

The apparent regulation of capillary pressure might also reflect a change in the postcapillary-precapillary resistance ratio \( R_R/J_R \). The arguments for this second explanation are as follows. Assume that the simple series resistance model, originally derived by Pappenheimer and Soto-Rivera (17), is a valid representation of the mesenteric vasculature so that mean capillary pressure can be defined by the relationship

\[
P_c = (R_R/R_a) \left( \frac{P_a + P_e}{1 + (R_R/R_a)} \right)
\]

where \( P_c, P_a, \) and \( P_e \) denote mean capillary pressure, arterial blood pressure, and venous pressure, respectively. \( R_R/R_a \) may be written in terms of these three pressures by rearranging Eq. 1.

\[
R_R/R_a = \frac{(P_e - P_c)}{(P_e - P_a)}.
\]

The relationship between the measured values for capillary pressure and systemic arterial blood pressure can be obtained from curve A. As stated previously, the equation of best fit was

\[
P_e = 0.043P_a + 28.34.
\]

The resistance ratio can be written in terms of two pressure variables by substituting the expression for capillary pressure (Eq. 3) into Eq. 2:

\[
R_R/R_a = \frac{(-0.043P_e - 21.34)}{(-0.0957P_e + 28.34)}.
\]

In our experiments, \( P_e \) was held constant at 7 mm Hg. Therefore, Eq. 4 may be written in terms of one pressure variable:

\[
R_R/R_a = \frac{(-0.043P_a - 21.34)}{(-0.0957P_a + 28.34)}.
\]

Values of \( R_R/R_a \) were calculated from Eq. 5 for known values of arterial blood pressure; the results are shown in Figure 6. It appears that the relatively constant capillary pressure can be explained as an increase in \( R_R/R_a \) as arterial blood pressure is reduced. Indeed, the predicted inverse relation-
Maintenance of a relatively constant capillary pressure in the mesentery may also have been the consequence of the repeating modular organization peculiar to this tissue. Frasher and Wayland (19) have described the arcade nature of the mesenteric vasculature and defined what they termed a module. The smallest identifiable unit module consists of an area of mesentery completely surrounded by an arteriole 20-30μ in diameter and a venule approximately 30-45μ in diameter. Frasher and Wayland (19) classified these vessels as zero-order arterial and venous vessels and referred to them as perimeter vessels of the module. Generally, four to six arteriole-arteriole and venule-venule connections join the perimeter vessels at points around the module. All capillaries are interior vessels of the module and receive blood from the perimeter arteriole. This structure allows a single capillary within a given module to receive blood from any of several inputs around the perimeter arteriole. It is comparable to a resistance bridge and ensures rapid redistribution of pressure and flow within the module. The capillary pressures which we observed may reflect the function of this structure. Figure 7 and 8 show the results of one series of measurements which illustrates this point.

The experimental procedure was carried out as described earlier in this paper. Systemic blood pressure was initially adjusted to approximately 100 mm Hg. In this case, control systemic blood pressure averaged 102 mm Hg and ranged (solid bar, Fig. 7) between 100 and 106 mm Hg during the experiment. A large arteriole (64/A) was identified, and its transmural pressure and dimensions were recorded. Systemic blood pressure was then decreased in 20 mm Hg steps. Transmural pressure decreased accordingly, and vessel diameter decreased passively. Systemic blood pressure was returned to control, and the procedure was repeated downstream in an arteriole (47μ), again in a terminal arteriole (28μ), and finally in an arterial capillary (10μ). The 28μ terminal arteriole was identified as a perimeter arteriole of a module (19), and the capillary was within the area bounded by this vessel. When systemic blood pressure was normal (102 mm Hg), the microvascular pressure (open circles, Fig. 7) decreased progressively from the large arteriole, through the terminal arteriole (perimeter vessel), to the capillary. Figure 8 is a schematic representation of the vascular connections and was reconstructed from the video recording of the microscope fields. Vessel lengths are not

**FIGURE 6**

Postcapillary-precapillary resistance ratio \( (R_v/R_a) \) vs. systemic arterial blood pressure \( (P_a) \) calculated from Eq. 5. Curve predicts the resistance ratio for a simple series resistance network which would account for the results in Figure 5 (bottom right, curve A). The shaded area represents the error introduced by the error in Figure 5 (bottom right, curve A).

ship between \( R_v/R_a \) and arterial blood pressure (Fig. 6) is consistent with previous observations reported by Johnson and Hanson (18) and therefore might be construed as a reasonable explanation for the apparent regulation of capillary pressure. However, this interpretation must be accepted with caution. Eq. 5 includes an empirical expression (Eq. 3) for the measured values of capillary pressure. It therefore predicts what \( R_v/R_a \) would have to be at each arterial blood pressure level to reproduce the mean capillary pressures actually measured. In other words, it essentially presupposes the values of \( R_v/R_a \) which will reproduce curve A according to the assumptions inherent in the simple series resistance model (17). Furthermore, the same resistance ratios shown in Figure 6 can be derived from a variety of different resistance models.

Resistance changes probably did contribute to the constant capillary pressures observed in Figure 5. However, it is not possible to conclude from these data alone whether the changes were active or passive, nor is it possible to distinguish which resistance vessels were primarily involved. Richardson and Zweifach (2) attempted to distinguish precapillary resistances in the cat mesentery by calculating the ratio of precapillary resistance to total resistance. Their calculations required an estimate of regional mesenteric flow. Unfortunately, they measured only total flow which includes parallel flow through the intestinal muscle and mucosa. Since their calculations assumed that total flow and mesenteric flow were equal, their interpretation is subject to question.

Circulation Research, Vol. XXXIV, April 1974
FIGURE 7
Example of one experiment showing steady-state pressure distributions as a function of mean diameter when systemic blood pressure was reduced in steps from a control pressure of 102 mm Hg to 81, 61, and 41 mm Hg. Solid vertical bars represent the extreme range in mean systemic blood pressure for each step. Open circles are the control pressures recorded in a 64μ large arteriole, 47μ arteriole, 28μ terminal arteriole, and a 10μ arterial capillary when systemic blood pressure was 102 mm Hg. The geometric arrangement between these vessels is shown in Figure 8.

FIGURE 8
Schematic representation of arrangement of vessels from which data in Figure 7 were recorded. Diagram shows direction of flow and measured values of mean diameter and pressure in large arteriole, arteriole, terminal arteriole (perimeter arteriole), and arterial capillary when systemic blood pressure (Pa) was 102 and 41 mm Hg. The illustration was derived from video recordings of microscope fields. The diagram is not drawn to scale. See text for further discussion.

It is apparent from Figures 7 and 8 that, when systemic blood pressure was between 102 and 81 mm Hg, capillary C was perfused from the arterioles entering at point A. The resistance of arterioles entering at point B must therefore have been greater than that of arterioles entering at point A. However, when systemic blood pressure was reduced to 41 mm Hg, capillary C was perfused from the arteriole path entering at point B. In this case, the resistance of arterioles entering at point A must have increased relative to that of arterioles entering at point B, even though the total precapillary resistance was probably less than control, as Figure 6 would indicate. Although these data describe only one series of measurements on a single module, they illustrate the functional influence which the structure of the mesenteric vasculature may have on capillary pressure. They also illustrate that, if capillary pressure is directly controlled by some purposeful mechanism, then its exact nature cannot be discerned from simple resistance calculations like those shown in Figure 6. The data must be interpreted in terms of the actual morphology of the microvascular bed. The results reported in this paper are insufficient to assert that...
capillary pressure as such is physiologically regulated. In fact, the data suggest that capillary pressures merely reflect vascular changes associated with flow regulation and the nature of the vascular architecture.

Acknowledgment

The author expresses his gratitude to Mrs. Cynthia J. Johnston for her excellent technical assistance.

References

Pressures in Cat Mesenteric Arterioles and Capillaries during Changes in Systemic Arterial Blood Pressure
ROBERT W. GORE

Circ Res. 1974;34:581-591
doi: 10.1161/01.RES.34.4.581

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 1974 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/34/4/581

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/