INTRAVITAL STUDY OF THE EFFECT OF MICROVASCULAR GEOMETRY ON DISTRIBUTION OF HEMATOCRIT READING AT BIFURCATIONS

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With a reduction in the diameter of capillary tubes, the hematocrit reading (HR) in them falls progressively (the Fahraeus effect). Meanwhile, *in vivo* a higher value of HR has been demonstrated in the capillaries, namely 30% [5, 7-9]. It is not yet clear why, with a reduction in the diameter of the vessels as they branch progressively, HR in them should remain at such a high level. Possibly microvascular geometry, which is one factor concerned in the regulation of the blood flow and diffusion of oxygen in them, may play a role in the mechanism of maintenance of HR [2-4, 6].

In the investigation described below an intravital comparative study of HR was made along the course of microvessels and in their bifurcations, and the effect of microvascular geometry on HR also was examined.

EXPERIMENTAL METHOD

Experiments were carried out on 30 noninbred male albino rats weighing 160-300 g, anesthetized with pentobarbital (0.1 g/kg intramuscularly). Intravital determination of the mo-

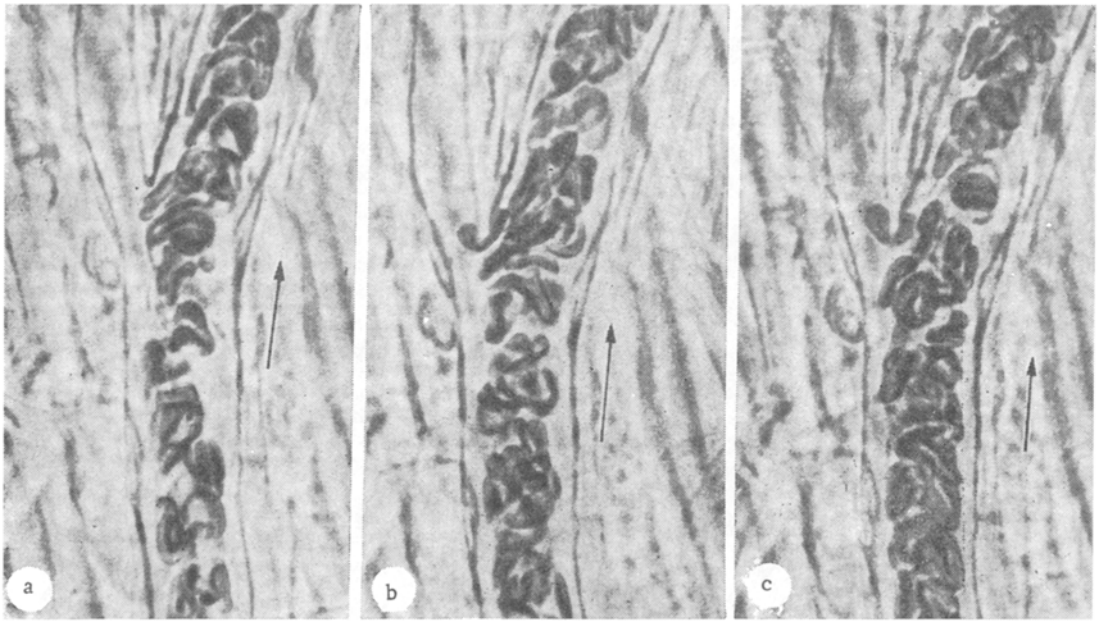

Fig. 1. Delay of an erythrocyte at a point of bifurcation. a) Blood flow along one branch of a bifurcation is rapid; b) an erythrocyte pressed against the fork of a microvessel; c) 5 sec after holdup of erythrocyte at point of bifurcation, the majority of its volume lies in the plasmatic vessel. Here and in Fig. 2, arrows indicate direction of blood flow. Biomicroscopy. Objective 70, ocular 3×.

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TABLE 1. Distribution of HR in Microvascular Bifurcations of Rat Mesentary with Different Branching Angles (bifurcations of group 1)

Microvessels	Number of animals	Number of bifurcations	Afferent vessel		First branch, continuation of vessel			Second branch		
			D, μ (1)	HR, ml/ml (2)	D_1, μ (3)	HR_1, ml/ml (4)	∠α°, (5)	D_2, μ (6)	HR_2, ml/ml (7)	∠β°, (8)
I. Arterioles	6	23	$17,9 \pm 0,6$	$0,37 \pm 0,02$	$15,3 \pm 0,9$ $P_{1-3} < 0,05$	$0,37 \pm 0,01$ $P_{2-4} > 0,1$	$23,1 \pm 4,3$	$11,2 \pm 0,8$ $P_{1,3-6} < 0,001$	$0,28 \pm 0,02$ $P_{2,4-7} < 0,001$	$68,9 \pm 6,5$ $P_{5-8} < 0,01$
II. Metarterioles	6	27	$12,4 \pm 0,2$ $P_{I-II} < 0,001$	$0,36 \pm 0,02$ $P_{I-II} > 0,1$	$11,5 \pm 0,5$ $P_{1-3} = 0,05$ $P_{I-II} < 0,001$	$0,35 \pm 0,02$ $P_{2-4} > 0,1$ $P_{I-II} > 0,1$	$29,8 \pm 4,8$ $P_{I-II} > 0,1$	$9,3 \pm 0,4$ $P_{1,3-6} < 0,001$ $P_{I-II} < 0,05$	$0,27 \pm 0,02$ $P_{2,4-7} < 0,001$ $P_{I-II} > 0,1$	$87,6 \pm 5,7$ $P_{5-8} < 0,001$ $P_{I-II} < 0,05$
III. Precapillaries	8	22	$9,8 \pm 0,3$ $P_{I,II-III} < 0,001$	$0,35 \pm 0,01$ $P_{I,II-III} > 0,1$	$9,2 \pm 0,4$ $P_{1-3} > 0,1$ $P_{I,II-III} < 0,001$	$0,32 \pm 0,02$ $P_{2-4} > 0,05$ $P_{I-III} < 0,05$ $P_{II-III} > 0,1$	$21,9 \pm 4,1$ $P_{I,II-III} > 0,1$	$8,6 \pm 0,3$ $P_{1-6} < 0,01$ $P_{3-6} > 0,1$ $P_{I-III} < 0,01$ $P_{II-III} > 0,1$	$0,25 \pm 0,02$ $P_{2,4-7} < 0,001$ $P_{I,II-III} > 0,1$	$89,5 \pm 7,9$ $P_{5-8} < 0,001$ $P_{I-III} < 0,05$ $P_{II-III} > 0,1$
IV. Capillaries	4	10	$8,3 \pm 0,3$ $P_{I,II,III-IV} < 0,001$	$0,25 \pm 0,04$ $P_{I,II-IV} < 0,01$ $P_{III-IV} < 0,02$	$7,8 \pm 0,2$ $P_{1-3} > 0,1$ $P_{I,II,III-IV} < 0,001$	$0,31 \pm 0,06$ $P_{2-4} > 0,1$ $P_{I,II,III-IV} > 0,1$	$28,8 \pm 4,0$ $P_{I,II,III-IV} > 0,1$	$7,4 \pm 0,3$ $P_{1-6} > 0,05$ $P_{3-6} > 0,1$ $P_{I-IV} < 0,001$ $P_{II-IV} < 0,01$ $P_{III-IV} < 0,02$	$0,20 \pm 0,05$ $P_{2,4-7} > 0,1$ $P_{I,II,III-IV} > 0,1$	$67,2 \pm 11,8$ $P_{5-8} < 0,001$ $P_{I,II,III-IV} > 0,1$

Legend. Here and in Tables 2 and 3, α and β denote branching angles.

TABLE 2. Distribution of HR in Microvascular Bifurcations of Rat Mesentary with Different Branching Angles (bifurcations of group 2)

Microvessels	Number of animals	Number of bifurcations	Afferent vessel		First branch, continuation of vessel			Second branch		
			D, μ (1)	HR, ml/ml (2)	D_1, μ (3)	HR_1, ml/ml (4)	∠α°, (5)	D_2, μ (6)	HR_2, ml/ml (7)	∠β°, (8)
I. Arterioles	4	18	$17,9 \pm 0,6$	$0,37 \pm 0,02$	$15,7 \pm 1,0$ $P_{1-3} < 0,05$	$0,32 \pm 0,02$ $P_{2-4} < 0,05$	$15,7 \pm 3,2$	$12,4 \pm 0,8$ $P_{1,3-6} < 0,001$	$0,41 \pm 0,01$ $P_{2-7} < 0,01$ $P_{4-7} < 0,001$	$74,4 \pm 8,0$ $P_{5-8} < 0,001$
II. Metarterioles	5	18	$13,0 \pm 0,1$ $P_{I-II} < 0,001$	$0,32 \pm 0,02$ $P_{I-II} < 0,05$	$12,0 \pm 0,4$ $P_{1-3} < 0,01$ $P_{I-II} < 0,01$	$0,28 \pm 0,02$ $P_{2-4} < 0,1$ $P_{I-II} < 0,05$	$27,2 \pm 5,5$ $P_{I-II} > 0,05$	$9,6 \pm 0,8$ $P_{1-6} < 0,001$ $P_{3-6} < 0,01$ $P_{I-II} < 0,02$	$0,36 \pm 0,01$ $P_{2-7} < 0,01$ $P_{4-7} < 0,001$ $P_{I-II} < 0,01$	$78,7 \pm 9,2$ $P_{5-8} < 0,001$ $P_{I-II} > 0,1$
III. Precapillaries	7	38	$9,6 \pm 0,2$ $P_{I,II-III} < 0,001$	$0,35 \pm 0,01$ $P_{I,II-III} > 0,1$	$8,9 \pm 0,1$ $P_{1-3} < 0,01$ $P_{I-III} < 0,01$ $P_{II-III} < 0,001$	$0,29 \pm 0,02$ $P_{2-4} < 0,01$ $P_{I,II-III} > 0,1$	$20,1 \pm 3,0$ $P_{I,II-III} > 0,1$	$9,0 \pm 0,3$ $P_{1-6} < 0,05$ $P_{3-6} > 0,1$ $P_{I-III} < 0,01$ $P_{II-III} < 0,1$	$0,39 \pm 0,01$ $P_{2-7} < 0,01$ $P_{4-7} < 0,001$ $P_{I-III} < 0,05$ $P_{II-III} > 0,1$	$81,3 \pm 5,7$ $P_{5-8} < 0,001$ $P_{I,II-III} > 0,1$
IV. Capillaries	3	3	$6,3 \pm 0,3$ $P_{I,II,III-IV} < 0,001$	$0,35 \pm 0,06$ $P_{I,II,III-IV} > 0,1$	$6,0 \pm 0,4$ $P_{1-3} > 0,1$ $P_{I,II,III-IV} < 0,001$	$0,24 \pm 0,09$ $P_{2-4} > 0,1$ $P_{I,II,III-IV} > 0,1$	$31,7 \pm 2,0$ $P_{I-IV} < 0,01$ $P_{II-IV} > 0,1$ $P_{III-IV} < 0,01$	$5,7 \pm 0,6$ $P_{1,3-6} > 0,1$ $P_{I,II,III-IV} < 0,001$	$0,39 \pm 0,01$ $P_{2,4-7} > 0,1$ $P_{I,II,III-IV} > 0,1$	$41,3 \pm 0,6$ $P_{5-8} < 0,02$ $P_{I,IIII-IV} < 0,01$

TABLE 3. Distribution of HR in Microvascular Bifurcations of Rat Mesentary with Different Branching Angles (bifurcations of group 3)

Microvessels	Number of animals	Number of bifurcations	Afferent vessel		First branch, continuation of vessel			Second branch		
			D, μ (1)	HR, ml/ml (2)	D_1, μ (3)	HR_1, ml/ml (4)	$\angle\alpha^\circ$, (5)	D_2, μ (6)	HR_2, ml/ml (7)	$\angle\beta^\circ$ (8)
I. Arterioles	3	3	$20,0 \pm 2,9$	$0,37 \pm 0,003$	$19,7 \pm 2,6$ $P_{1-3} > 0,1$	$0,35 \pm 0,03$ $P_{2-4} > 0,1$	$10,7 \pm 2,6$	$10,8 \pm 3,1$ $P_{1,3-6} > 0,05$	$0,35 \pm 0,04$ $P_{2,4-7} > 0,1$	$39,3 \pm 10,7$ $P_{5-8} < 0,05$
II. Metarterioles	2	4	$12,8 \pm 0,5$ $P_{I-II} < 0,05$	$0,39 \pm 0,02$ $P_{I-II} > 0,1$	$11,1 \pm 0,8$ $P_{1-3} > 0,1$ $P_{I-II} > 0,1$	$0,39 \pm 0,03$ $P_{2-4} > 0,1$ $P_{I-II} > 0,1$	$22,8 \pm 7,4$ $P_{I-II} > 0,1$	$8,8 \pm 1,3$ $P_{1-6} < 0,05$ $P_{3-6} > 0,1$ $P_{I-II} > 0,1$	$0,39 \pm 0,03$ $P_{2,4-7} > 0,1$ $P_{I-II} > 0,1$	$90,8 \pm 19,7$ $P_{5-8} < 0,02$ $P_{I-II} > 0,1$
III. Precapillaries	6	9	$10,1 \pm 0,5$ $P_{I,II-III} < 0,01$	$0,34 \pm 0,04$ $P_{I,II-III} > 0,1$	$9,9 \pm 0,7$ $P_{1-3} > 0,1$ $P_{I-III} < 0,05$ $P_{II-III} > 0,1$	$0,37 \pm 0,03$ $P_{2-4} > 0,1$ $P_{I,II-III} > 0,1$	$27,2 \pm 6,7$ $P_{I,II-III} > 0,1$	$9,3 \pm 0,9$ $P_{1,3-6} > 0,1$ $P_{I,II-III} > 0,1$	$0,36 \pm 0,04$ $P_{2,4-7} > 0,1$ $P_{I,II-III} > 0,1$	$57,2 \pm 8,7$ $P_{5-6} < 0,02$ $P_{I,II-III} > 0,1$
IV. Capillaries	3	3	$8,0 \pm 0,6$ $P_{I-IV} < 0,001$ $P_{II-IV} < 0,01$ $P_{III-IV} < 0,05$	$0,29 \pm 0,03$ $P_{I-IV} < 0,05$ $P_{II-IV} < 0,02$ $P_{III-IV} > 0,1$	$8,0 \pm 0,6$ $P_{1-3} > 0,1$ $P_{I-IV} < 0,02$ $P_{II-IV} < 0,05$ $P_{III-IV} > 0,05$	$0,34 \pm 0,02$ $P_{2-4} > 0,1$ $P_{I,II,III-IV} > 0,1$	$27,0 \pm 3,5$ $P_{I-IV} < 0,02$ $P_{II,III-IV} > 0,1$	$8,0 \pm 0,6$ $P_{1,3-6} > 0,1$ $P_{I,II,III-IV} > 0,1$	$0,36 \pm 0,03$ $P_{2,4-7} > 0,1$ $P_{I,II,III-IV} > 0,1$	$64,0 \pm 10,5$ $P_{5-8} < 0,05$ $P_{I,II,III-IV} > 0,1$

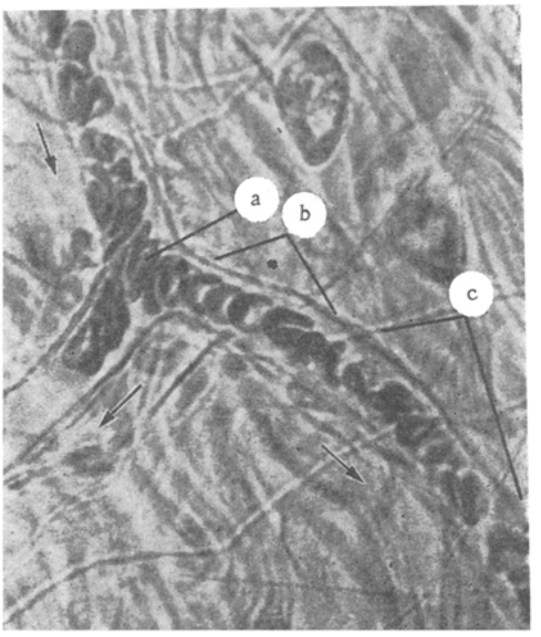

Fig. 2. Increase in hematocrit reading in precapillary (D = 9 μ) before bifurcation: a) accumulation of erythrocytes, stretched transversely to axis of the vessel, in a region of bifurcation; b) HR = 0.37 ml/ml before the bifurcation; c) HR = 0.21 ml/ml along length of capillary. Biomicroscopy. Objective 40, ocular 3×.

mentary value of HR in the mesenteric microvessels of the rat intestine was undertaken by the method in [1], but with a more powerful optical system: objective 70, ocular 3. HR was determined in 124 areas along the length of the microvessels, and in 217 bifurcations (in 178 with different branching angles, in 39 with identical angles). The numerical results were subjected to statistical analysis by Student's method.

EXPERIMENTAL RESULTS

Along the length of the microvessels the following results were obtained: in arterioles with diameter (D) 15.5 ± 0.6 μ HR = 0.26 ± 0.04 ml/ml (n = 11, number of vessels), in metarterioles with D = 12.6 ± 0.1 μ HR = 0.34 ± 0.03 ml/ml (n = 15), in precapillaries with D = 10.0 ± 0.1 μ HR = 0.30 ± 0.01 ml/ml (n = 40), in capillaries with D = 9.1 ± 0.4 μ HR = 0.11 ± 0.1 ml/ml (n = 17), and in arteriolovenular anastomoses with D = 7.6 ± 0.3 μ HR = 0.44 ± 0.02 ml/ml (n = 41). Despite the difference in the diameters of the vessels studied, values of HR in arterioles, metarterioles, and precapillaries did not differ significantly ($P < 0.05$).

In order to find the explanation of the fact, HR was studied in a microvascular bifurcation, which is an important structural element of the vascular tree. The results obtained showed that HR in afferent arterioles, precapillaries, and capillaries before a bifurcation (Tables 1 and 2) is higher than HR of the same vessels, determined along their length ($P < 0.01$). During biomicroscopy and in photomicrographs of afferent vessels of bifurcations delay of the blood cells (mainly erythrocytes) and an increase in their density and number were observed; slowing of the blood flow and dilatation of the lumen of the vessels before branching could be seen visually. These changes were due primarily to mechanical obstruction to the blood flow, created by branching of the microvessel (Figs. 1 and 2). The increase in HR before each branching of the microvessels contributed toward maintaining it in the vascular ramifications at a sufficiently high level, and prevented the progressive decline of HR during successive branching of the microvessels.

According to the distribution of HR in the branches, all the bifurcations studied could be divided into four groups: bifurcations of the first three groups had different branching angles, those of group 4 had identical angles. Groups 1 and 2 included bifurcations in which the distribution of HR in the branches depended on their branching angle: in group 1 (46% of bifurcations with different branching angles) HR was greater in the branch given off

at a smaller angle (Table 1), whereas in group 2 (43% of bifurcations) HR was greater in the branch given off at a greater angle (Table 2). In group 3, the smallest (19 bifurcations, or 11%) HR was equal in the branches of the bifurcations (Table 3).

Comparison of the groups of bifurcations given above showed that group 1 consisted of bifurcations whose branches were not anastomoses, whereas the second branches of the group 2 bifurcations were anastomoses. The writers showed previously that HR along the length of anastomoses has a higher value than HR of any other microvessels [5]. This particular feature also is observed when the anastomosis is one branch of a bifurcation. Despite the greater branching angle, whereas anastomoses as a rule branch off at an obtuse angle or close to a right angle, HR in an anastomosis branch is higher in value than HR of the other branch which is a continuation of the afferent vessel of the bifurcation. Bifurcations of group 3 are evidently intermediate between groups 1 and 2, and they may be associated with periodic functions of one of the branches of a bifurcation in the role of an anastomosis.

Group 4 included bifurcations with identical branching angles and an equal value of HR (about 0.30 ml/ml) in different vessels and in different branches. This group consisted mainly of precapillary and capillary bifurcations.

The data on distribution of HR in the microvascular network of the mesentery are evidence of the complexity and diversity of distribution of HR, which depends not only on the branching angle of the vessel and its diameter, but also on the functional role of the microvessel. At the same time, a strict pattern of distribution of HR can be discerned, which takes into account not only the geometric parameters of the vessels, but also their functions.

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