BLOOD-FLOW DISTRIBUTION AT BRANCHES OF ARTERIAL MICROVESSELS IN THE FROG MESENTERY

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The blood-flow distribution was studied in 49 bifurcations of arterial trunks 25.7 μ in diameter into branches 0.9 μ in diameter in the mesentery of *R. temporaria*. The flow was calculated as the product of the linear velocity of blood flow and the area of cross-section of the vessel. The linear velocity was measured by impulse digital chronometry of the erythrocyte transit time, and the geometry of the bifurcation was studied in intravital photographs. The asymmetrical structure of the bifurcation was established: One branch had a lumen 2.2 times greater than the other, and a smaller angle of turn (29° and 59°). The flow into branch I was 3 times greater than the flow into branch II, as the result of its larger lumen and the greater linear velocity of the blood flow. According to calculations, the specific resistance of turn of the branch was negligible compared with the total resistance to its blood flow; hence it follows that the angle of turn of the branches is not an important regulator of the blood volume flowing through it. The correlation found experimentally between the blood flow in the branches, their radius, and their angle of turn is well described by equations of an "optimal" model of vascular ramification.
KEY WORDS: *microcirculation; mesentery; velocity of blood flow; resistance to blood flow; architectonics of the vascular system.*

The many publications of the results of model experiments and papers devoted to mathematical models of the blood flow [2, 4, 7] highlight the inadequacy of our knowledge of the concrete structure of the vascular system in the organs and the effect of its particular features on the blood flow distribution at bifurcations of blood vessels. This applies to the mesentery, where the hemodynamics has perhaps been studied in the greatest detail [3, 5, 6, 8, 9].

TABLE 1. Linear Velocity of Blood Flow in Mesenteric Arterial Microvessels of Spring Frogs (*R. temporaria*) (M±m)

Diameter of vessel (in μ)	Velocity of blood flow (in μ/sec)		
	main trunk	branches	overall
15	—	340±60 (17)	340±60 (17)
16—20	500±115 (7)	310±50 (30)	350±30 (37)
21—25	420±80 (12)	320±80 (19)	360±40 (31)
26—30	400±70 (18)	380±50 (23)	390±40 (41)
31—40	430±50 (12)	360±75 (9)	410±50 (21)
Overall	420±40 (49)	340±30 (98)	—

Note. Number of vessels measured shown in parentheses.

Data on the structure and character of the blood flow in the last three or four ramifications of the mesenteric arteries, in which as a rule capillaries are formed, are described below.

EXPERIMENTAL METHOD

Experiments were carried out on frogs (*Rana temporaria*) immobilized by subcutaneous injection of diplacin dichloride in a dose of 100 mg/kg. The mesentery with a loop of intestine was exteriorized through an abdominal incision and laid on the glass slab of the moving stage of a microscope under a transparent polystyrene film.

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TABLE 2. Morphological and Functional Characteristics of Mesenteric Arterial Bifurcation in *R. temporaria* with Trunk 25.7 μ in Diameter ($M \pm m$)*

Index studied	Branch I	Branch II
Diameter of branch/ diameter of trunk	0,98±0,01	0,65±0,02
Cross section of branch as a fraction†	0,69±0,02	0,31±0,02
V_{branch}/V_{trunk} ‡	0,79±0,04	0,62±0,05
Flow in branch as a fraction**	0,74±0,02	0,26±0,05
Angle of turn of branch φ	29±3°	59±6°
Coefficient of branching††	1,38±0,11	
Coefficient of correlation: between fraction of flow in branch and fraction of its cross-section	0,88±0,02	
Between fraction of flow in branch and its angle of turn	—0,74±0,01	
Between diameter of branch and its angle of turn	—0,70±0,05	

*For 49 bifurcations m = 0.9

†Relative to combined areas of cross section of both branches

‡V denotes linear velocity of flow

**Relative to combined flow in both branches

††Ratio between combined areas of cross section of branches and cross section of trunk.

With the apparatus described previously, the mean linear velocity of the blood flow over a period of 10 sec was measured. Measurements were made consecutively in each of three vessels forming a bifurcation of the vascular tree; the main trunk, the wider branch (branch I), and the narrower branch (branch II). The cycle of measurements was repeated from 2 to 8 times depending on the stability of the blood flow. The mean harmonic velocity along each vessel was used in the calculations. The diameters of the vessels and their angles of turn were measured from photographs taken *in vivo*. The volume velocity of the blood flow was calculated as the product of the linear velocity and the area of cross section; it was assumed that errors due to the elliptical shape of the lumen and the parabolic profile of the velocities in the flow were the same for all vessels of the bifurcation, and that they did not therefore distort the patterns of distribution of flow in them.

EXPERIMENTAL RESULTS AND DISCUSSION

The circulation in *R. temporaria* is extremely unstable (Table 1). However, fluctuation in the velocity of the blood flow in the system of mesenteric arteries ought not to have any significant effect on the character of blood flow distribution in the bifurcations, more especially because the measurements were made on vessels with no visible pathology. These experiments satisfied the condition of continuity of flow: The ratio between the combined flow in the two branches and the flow in the main trunk in all 49 bifurcations was 1.00 ±0.03.

The similarity of anatomical construction of the bifurcations studied and their roughly similar localization in the mesenteric arterial system make it possible to give the general characteristics for vascular ramifications of this type (Table 2). Their structure is asymmetrical: Branch I has a larger lumen and a smaller angle of turn than branch II. Correlation between the angle of turn and the diameter of the branch is characterized by a high negative coefficient. The asymmetry of structure of the vascular ramifications gives rise to asymmetry in the distribution of the blood flow between the branches. The flow in branch I was about three times greater than the flow in branch II, on account not only of its wider lumen, but also its higher linear velocity of flow. Hence it follows that the resistance of the system of branch I to the blood flow was on the average only one-third of the resistance of the system of branch II.

Considering the high coefficient of negative correlation between the fraction of the blood flow in a branch and its angle of turn, the role of the local resistance of turn as a contribution to the total resistance of the branch had to be evaluated. Levick's formula [1] gives an approximate value for local losses due to turning ζ_T in an expanding bifurcation for which $V_{branch}/V_{trunk} < 0.8$* (all subsequent calculations were carried out in accordance with data in Tables 2 and 3):

$$\zeta_T \; 1 + (V_{branch}/V_{trunk})^{\dagger} - 2V_{branch}/V_{trunk} \cos\phi. \quad (1)$$

*Equation (1) was deduced for the flow of liquids with Re > 1000. It is evident that for laminar flows, such as the blood flow in small vessels, the coefficient ζ_T will be smaller still. Equation (2) describes the laminar flow of liquids.

TABLE 3. Mean Values of Morphological and Functional Indices for 49 Bifurcations Used in Calculations

Index	Trunk	Branch I	Branch II
Radius r (μ)	12,9	12,6	8,3
Area of cross section S (μ^2)	523	499	216
Velocity of blood flow V (μ /sec)	420	330	260
Flow f (in μ^3/sec)	220	165	56
Reynolds' number (Re) (given viscosity of blood 4 cP, density 1.06 g/cm^3)	0,014	0,011	0,006

For branch II, $\zeta_T = 0.3$. This is very small if it is compared with the loss due to friction of the blood flowing along this branch ζ_F [1] (given that its length is 50 times the diameter [5]):

$$\zeta_F = (50 \times 64)/\mathrm{Re}, \tag{2}$$

$\zeta_F = 53 \times 10^5$ and is 18×10^6 times greater than ζ_T. The actual contribution of the resistance due to turning of the branch to its total resistance to the blood flow is thus very small. Hence it follows that the angle of turn of the smallest branches of the mesenteric arteries cannot act as an important regulator of the volume of blood flowing in them.

The close correlation between the fraction of the flow in the branches and their angle of turn is evidently not direct, but mediated through an equally close correlation between the fraction of the flow and the diameter of the branch (Table 2). The existence of this correlation can be predicted by mathematical analysis of the optimal construction of a vascular bifurcation [2, 4, 7]. In such a bifurcation the total expenditure of energy in maintaining the structure and the blood flow must be minimal. The model of the "optimal" vascular bifurcation requires that the flows in the trunk and branches are related to their radii by the equation:

$$r_0^3/f_0 = r_1^3/f_1 = r_2^3/f_2 = \text{const}^* \tag{3}$$

and the angles of turn of the branches depend on the radii of the branches and trunk as follows:

$$\cos\varphi_1 = \left(r_0^4 + r_1^4 - r_2^4\right)\cdot 0{,}5\, r_0^{-2}\cdot r_1^{-2};$$
$$\cos\varphi_2 = \left(r_0^4 + r_2^4 - r_1^4\right)\cdot 0{,}5 r_0^{-2}\cdot r_2^{-2}. \tag{4}$$

In the vessels of this "average" bifurcation, the values of the ratio r^3/f are approximately 0.0098, 0.0121, and 0.0102, and the angles of turn of the branches (Table 2) are close to their calculated values (72 and 25°). The construction of this model can accordingly be regarded as close to "optimal.".

LITERATURE CITED

1. I. E. Idel'chik, Reference Book on Hydraulic Resistances [in Russian], Moscow–Leningrad (1960).
2. R. Rosen, Optimality Principles in Biology [Russian translation], Moscow (1969).
3. J. F. Gross, M. Intaglietta, and B. W. Zweifach, Am. J. Physiol., 226, 1117 (1974).
4. A. Kamiya, T. Togawa, and A. Yamamoto, Bull. Math. Biol., 36, 311 (1974).
5. E. M. Landis, Am. J. Physiol., 103, 432 (1933).
6. J. P. Mall, Abhandl. math. phys. Classe Königl.-sächs. Ges. Wiss., 14, 153 (1887).
7. C. D. Murray, Proc. Nat. Acad. Sci. (Washington), 12, 204 and 299 (1926).
8. D. Vanter, Y. C. Fung, and B. W. Zweifach, Microvasc. Res., 8, 44 (1974).
9. B. W. Zweifach, Circulat. Res., 34, 843 (1974).

*0, 1, 2 represent indices for trunk and branches I and II respectively.