STATIC AND DYNAMIC CHARACTERISTICS OF THE FACTORS DETERMINING HYDRAULIC RESISTANCE IN THE SYSTEM OF PIAL ARTERIES

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Geometric parameters of the pial arterial system after intravital fixation in vivo were studied in rabbits. With a decrease in the caliber of the arteries the frequency of branching and the size of its angles increased, the total area of cross section of the branches decreased (consequently, the velocity of the blood flow in them increased relatively), and the mass of the media of the vessel walls (expressed as the ratio between the thickness of the wall and the diameter of the lumen) became greater. Most of the changes mentioned above were particularly marked in arteries with a caliber of under 100 μ. The degree of vasodilation (studied by serial intravital photomicrography, at a time of increased metabolic demand of the cerebral cortex) was also particularly great in arteries 50-100 μ in diameter. Consequently, in the pial arterial system the smallest vessels must play a particularly important role in the regulation of the cortical microcirculation.

The small pial arteries, located on the surface of the cerebral hemispheres, are particularly interesting from the standpoint of control of the cortical microcirculation, for lying within relatively wide channels filled with cerebrospinal fluid [1] they are the principal vascular mechanism controlling the cortical blood supply [5].

The object of this investigation was to make a quantitative assessment (a) of the static characteristics of the pial arterial system, i.e., of their geometry (length, width, angles of branching, and so on), and (b) its dynamic characteristics, i.e., the ability of arteries of different caliber to change their diameter under natural conditions of regulation of the cortical blood supply.

EXPERIMENTAL METHOD

Adult rabbits of both sexes weighing 1.5-2.5 kg (over 100 animals) were used. The operation was performed under local procaine anesthesia or general urethane anesthesia (up to 1 g/kg body weight).

To study the geometry of the pial arterial system 2 catheters were introduced into one of the carotid arteries (usually the right) after division of all branches except the internal carotid; 1 catheter was introduced in the cranial direction for the intravital injection of fixing fluid into the cerebral vascular system under constant pressure (100-120 mm Hg) and the other in the thoracic direction, for the simultaneous removal of blood from the aorta (to prevent elevation of the systemic arterial pressure, preventing the fixing fluid from entering the blood vessels of the brain). A ligature was placed around the second common carotid artery so that it could be occluded during the period of fixation [6]. A wide burr-hole was drilled in the parietal region to allow visual observation on the passage of the fixing fluid. In some experiments the pial arterial system was fixed by irrigating the brain surface in vivo with fixing fluid, when not only the width of the blood vessels but also the axial flow of erythrocytes could be studied [4]. After the end of the preliminary fixation of the cerebral vessels the brain was removed from the skull and postfixed in 6-10% formalin

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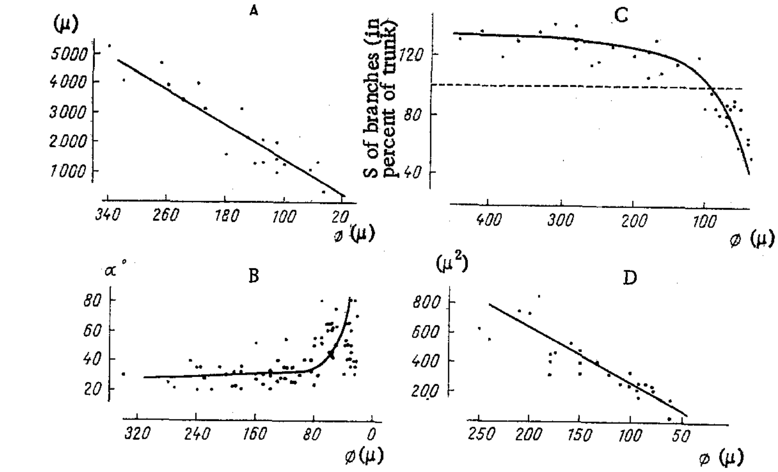

Fig. 1. Geometric characteristics of the branching system of the pial arteries of the rabbit: A) distance between bifurcations (ordinate) as a function of caliber (diameter) of trunk (abscissa); mean confidence limits m = ±5; B) branching angles (ordinate) as a function of caliber of main trunk (abscissa); m = ± 8.9; C) changes in total area of cross section of vessels after branching (in percent of area of trunk; (ordinate) as a function of caliber of main trunk (abscissa); m = ±4.8; D) area of cross section of side branches of pial arteries (ordinate) as a function of caliber of main trunk (abscissa); m = ±22.8.

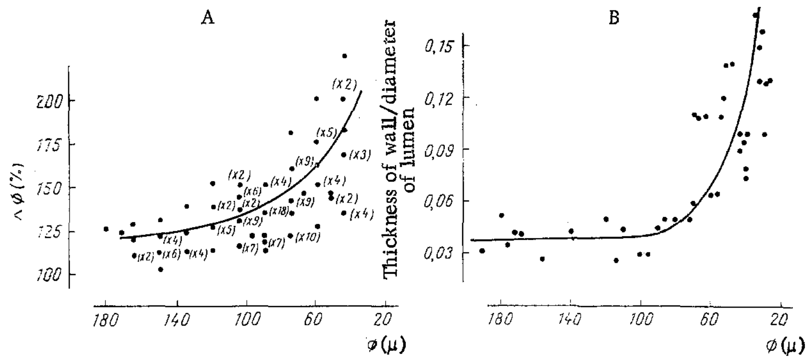

Fig. 2. Degree of dilation of rabbit pial arteries (in percent of initial diameter, ordinate) as a function of caliber (diameter) of vessels (abscissa) at a time of increased metabolic demand of the cerebral cortex (A) and mass of vascular media, expressed as the ratio between the thickness of the wall and the diameter of the lumen of the arteries (ordinate), as a function of caliber of the arteries (abscissa); m = ±2.7. Numbers in figures denote number of coinciding points (m = ±4.9). Explanation in text.

solution for 5-10 days. Under the MBS-2 binocular microscope the pia mata was carefully removed from the brain by means of dissection needles and forceps, spread out on a slide, and total preparations were made from it with the pial arteries already fixed in it [7]. These arteries were studied either in the unstained state or after staining with hematoxylin and alcoholic eosin, to reveal the axial flow of the erythrocytes selectively. The general geometry of the branching system of pial arteries was studied from drawings made with a drawing apparatus through the microscope or by photomicrography and subsequent measurements of the branching angles of the vessels; the length and caliber of individual arteries were measured directly in the preparations under the MBS-2 microscope with the aid of an ocular micrometer.

To study the dynamic characteristics of the pial arteries of different caliber the degree of their dilation was measured under various conditions, when the metabolic demand of the cerebral cortex was increased: a) after its activity had been increased by local application of 0.5% strychnine; b) after the blood supply had been reduced through a stepwise decrease in the systemic arterial pressure to 40 mm Hg; c) during postischemic hyperemia, arising after total interruption of the cerebral circulation for 1-2 min or a marked decrease in the blood flow for 15 min; and d) during respiratory hypoxia and hypercapnia (asphyxia) produced by closing the tracheotomy tube for about 1 min. Under these conditions serial photomicrographs were taken of the brain surface at intervals of 5-10 sec and the diameter of the pial arteries then measured in each frame on the film, so that the complete dynamics of the changes in width of the pial arteries could be determined. Some of the data given in this paper for the width of the pial arteries of the different caliber have been published previously [2, 3, 8, 9].

All the numerical results were subjected to statistical analysis using Student's criterion of significance [10].

EXPERIMENTAL RESULTS

The diameter of the vessels in the pial arterial system of rabbits ranges from 300 to 400 μ (initial parts of the anterior, middle, and posterior cerebral arteries) to 40-50 μ (terminal branches and interarterial anastomoses).

Two types of branches are found in the pial arterial system: first, branches (bifurcations) in which the trunk divides into two branches of more or less equal diameter (the ratio between the calibers of the branches is 0.84 ± 0.09), at more or less equal angles of the order of 30-50°, and second, small branches leaving the larger trunks at an angle of almost 90°. Throughout the length of the pial arteries (in adult rabbits of average weight their total length from the circle of Willis to the terminal branches in the parietal region is about 30-40 mm), with a decrease in caliber of the vessels the distance between the points of branching gradually decreases (Fig. 1A); i.e., the frequency of branching increases. The angles at which the branches leave the main trunk increased with a decrease in caliber of the pial arteries. This rule was observed throughout the pial arterial system and also at individual branching points where one branch as a rule was smaller in diameter and left the main trunk at a greater angle. The increase in the branching angles was particularly great in the region of the small pial arteries less than 100 μ in diameter (Fig. 1B).

In the case of bifurcation of relatively large pial arteries the total area of their cross section increases. This must lead to a corresponding decrease (in accordance with the law of continuity) in the velocity of the blood flow in the branches. However, this occurs only in arteries over 100 μ in diameter. At division of the arteries the ratio between the total area of the branches and the area of the main trunk decreased with a decrease in caliber of the vessels and was less than unity at branching of arteries under 100 μ in diameter (Fig. 1C). The same result was observed for the width of the axial flow of erythrocytes, which under normal conditions is a linear function of the width of the lumen of the vessel. This means that in the smallest pial arteries after bifurcation the velocity of the blood flow in the branches must increase relatively. In the case of branching of small pial arteries from large trunks the total area of the branching vessels per unit length of trunk is shown in Fig. 1D.

The geometric parameters of the pial arterial system are thus such that the resistance under steady-state conditions must be maximal in vessels with a diameter of under 100 μ, for the frequency and size of the angles of branching (where the disturbance of the flow conditions must create further resistance), and also the velocity of the blood flow, are maximal in the region of the smallest branches at bifurcation.

In connection with an increase in the metabolic demand of the cortex (during a sudden increase in the intensity of its metabolism, during primary circulatory failure, in the postischemic period, or in asphyxia), the smaller the caliber of the pial arteries the greater the degree of their dilation in the process of regulation of the microcirculation; this was seen particularly clearly in arteries under 100 μ in caliber (Fig. 2A). The strongest dilator stimuli and the strongest vascular responses during regulation of the cortical blood supply must therefore also be found in the smallest pial arteries. This corresponds completely to the mass of the arterial wall (most of which is formed by the muscular coat): with a decrease in caliber of the pial arteries the ratio between the thickness of the wall and the diameter of the lumen increases; this increase is particularly marked in arteries under 100 μ in caliber (Fig. 2B).

Consequently, the static and dynamic characteristics of the pial arterial system show that the principal role in the regulation of the cortical blood supply must be paid by their smallest branches. In rabbits the distance between the precortical arteries branching from the small pial arteries and entering the cortex averages 229 ± 11.5 μ. Consequently, the smallest pial arteries can regulate the blood flow in very small areas of the cortex. In more highly developed animals (for example, dogs and cats) and, in particular, in man the density of the network of pial arteries is much greater and the areas of the cortex whose blood supply can be regulated by individual pial arteries must be correspondingly smaller.

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