Perforating Branches of the Middle Cerebral Artery
Microanatomy and Clinical Significance of Their Intracerebral Segments

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SUMMARY Perforating branches of the middle cerebral arteries (MCA) were examined on the forebrain hemispheres of fourteen human brains. It was noticed that their intracerebral segments arose from the MCA main trunk, and its terminal and collateral (cortical) branches. They terminated in certain parts of the basal ganglia and internal capsule. The course, direction, shape, diameters and branches of these segments were examined in detail. Classification of all the vessels was made according to caliber. It was concluded that the size of lacunar infarcts depends on the caliber and ramification zone extent of the occluded perforating vessels. Diameters of the intracerebral segments of vessels ranged from 80 to 840 μm, of their terminal branches from 80 to 780 μm, and of the collateral branches from 50 to 400 μm. The average size of the ramification zone was: 41.6 x 15.5 mm for the entire perforating artery; 37.9 x 15.5 mm for the intracerebral segment; 23 x 13 mm for the terminal branches; 8.9 x 5.5 mm for larger collateral branches; and 2.6 x 1.4 mm for the smallest branches.

THE PERFORATING (central, lenticulostriate) vessels are branches of the proximal part of the middle cerebral artery. We have divided their stems into the extracerebral and intracerebral portions. The extracerebral segments (ES) run from the middle cerebral artery to the level of the anterior perforated substance, whereas the intracerebral segments (IS) extend from the anterior perforated substance to their terminations in certain portions of the basal ganglia and internal capsule.

The intracerebral segments are often affected by some vascular diseases, which can result in ischemic disorders or hemorrhages.1-4 These lesions in the central hemispheric regions can be identified by using magnification angiography, computed tomography and other diagnostic methods.5-9 All this, however, requires an excellent knowledge of the microanatomy of perforating arteries. Although these vessels have been described by many authors,10-14 there is still a lack of detailed anatomical information about their intracerebral segments.

Material and Methods

Fourteen brains of individuals aged from 31 to 65 years were used in this study. One of the individuals had suffered from the systemic arterial hypertension. The middle cerebral artery (MCA) of each hemisphere was selectively injected. Before injection, the initial portions of the anterior cerebral, posterior communicating and anterior choroidal arteries were ligated. The remains of blood in the MCA vascular bed were washed out with isotonic saline solution. Thereafter, a solution of methacrylic resin was prepared by mixing plastic resin monomer and polymerizer in 8:2 ratio.15 The mixed solution was rapidly injected into the middle cerebral artery. Ten milliliters of solution were usually sufficient to fill up the MCA bed. Because of rapid handling of the solution, air bubbles appeared in some cases, but without any influence on the accuracy of our results. An hour later, that is, when the polymerization of injected methacrylic resin was completed, the whole hemisphere was immersed in 6 liters of 40% potassium hydroxide. After three days, the used solution was replaced by a fresh solution of potassium hydroxide. Ten days later, when the brain tissue was dissolved, the plastic vascular cast was carefully washed in running water. All the cortical branches of the MCA were cut, in order to expose the perforating vessels (their plastic cast, respectively). After drying them, the specimens were examined under the stereoscopic microscope. Drawings of the perforating branches of every middle cerebral artery were made. The length and calibers of vessels were measured using the ocular micrometer.

Results

The intracerebral segments (IS) of the perforating branches of the middle cerebral artery (MCA) can be divided into two portions: the proximal (IS1) and the distal (IS2) (fig. 1). The border between them represents a well shaped curve or a real loop occasionally. There are differences in the position, course, calibers and ramification between the two portions.

Proximal Portions of the Intracerebral Segments (IS1)
a) Origin

The intracerebral segments arise by means of their extracerebral portions from the MCA main trunk, its terminal and collateral branches, from the common stems of the perforating vessels, or from some strong perforating arteries.

1. The perforating vessels most commonly originate from the dorsal surface of the MCA trunk (fig. 2).
PERFORATING BRANCHES OF MCA/Marinkovic et al

FIGURE 1. The plastic cast of some perforating branches of the middle cerebral artery (MCA). The branches have two segments: the extracerebral (ES) and intracerebral. The intracerebral portions are subdivided into the proximal (IS₁) and distal segments (IS₂). Note a loop of the smallest artery just proximal to the border between its IS₁ and IS₂ segments. Solid arrows indicate the collateral (cortical) branches, and open arrows point to the terminal (insular) stems of the MCA. ICA — the internal carotid artery; ACA — the anterior cerebral artery. The right MCA. Rostral view. (Magnification 3×).

Two, three, four (fig. 4) or more such single arteries can be present. The arteries arising from the same common stem are sometimes of different calibers.

5. Large perforating arteries occasionally give rise to several thin intracerebral arteries in the form of collateral vessels (fig. 5).

b) Course and Relationship to the Extracerebral Segments

The individual perforating arteries, after taking origin in the described manner, run toward the anterior perforated substance and converge above the medial half of the MCA. Just before entering the anterior perforated substance, these extracerebral segments (ES) change their courses, that is, they turn sharply dorsally (fig. 6), forming curves or real loops (fig. 5 and 6), which are located in the horizontal, coronal or an oblique plane. At the same time, the rearrangement of the perforating arteries begins. Namely, the extracerebral segments comprise three groups of vessels: the medial, middle and lateral. On the other hand, the IS, stems are positioned in such a manner as to form two groups: the lateral and medial; each of them can be further divided into a rostral and caudal subgroup. Accordingly, three groups of the extracerebral segments give rise to two main groups (four subgroups, respectively) of the intracerebral portions. The rearrangement pattern usually is as follows: the medial ES stems become the rostromedial, and especially caudomedial IS₁; the middle ES (and those lateral ES originating most rostrally from the MCA) give rise to the rostrolateral IS₁; the remaining lateral ES become the caudolateral IS₁. As a rule, the number of the rostral IS₁ stems is larger than the caudal ones.

Because of their different directions, more or less acute angles are formed between the ES and IS₁ stems. The mean value is 69°, minimum 25° and maximum 138°. The corresponding angles are also present between the IS₁ and the MCA main trunk. Their mean value is 55°, minimum 32° and maximum 105°. The
angle values are in general lower within the lateral group of the intracerebral segments.

The lateral intracerebral segments almost always take a lateral and dorsal direction (fig. 6). The medial IS, stems have a dorsal, but only slightly lateral course. In addition, the anterior IS, of both groups of vessels extend also rostrally, and the posterior ones run progressively caudally (fig. 7). Because of such an orientation, the IS, stems form a narrow and concave fan directed both rostrocaudally and mediolaterally (fig. 7). Its concavity is medially, dorsally and caudally directed. The mean value of the angle between the most rostral and the most caudal IS, stem of the fan is 44° (minimum 28°; maximum 80°).

c) Measurements

The average length of all the IS, stems is 7.1 mm (minimum 4.5 mm; maximum 10.2 mm). The average length of the lateral stems is 7.9 mm (minimum 5.0 mm; maximum 10.2 mm). The medial vessels are short: the mean value is 6.3 mm, minimum 4.5 mm and maximum 8.2 mm.

The greatest differences between the vessels within the lateral and medial group are in their diameters. The lateral IS, stems are approximately two times larger than the medial vessels:

Diameters of the lateral IS, stems

- mean value 510 µm
- minimum 120 µm
- maximum 840 µm

Diameters of the medial IS, stems

- mean value 280 µm
- minimum 90 µm
- maximum 480 µm
Figure 6. Arrangement of the proximal intracerebral segments. Both lateral and medial (arrowheads) arteries are arranged rostrocaudally and mediolaterally. MCA — the right middle cerebral artery. Rostral view. (12 X).

Two more facts should be mentioned about the vessels of the lateral group. First, 60% of their IS, stems have diameters of 500–840 μm in size. Second, the rostral IS, stems are, on the average, about 100 micrometers larger than the caudal IS,.

d) Branching

The proximal portions of the intracerebral segments almost exclusively give rise to the collateral branches, which are of the two kinds: the longitudinal and the transverse.

The longitudinal branches usually originate from the medial surface of the parent vessels. Some of them run along the IS, stems (fig. 8). The others extend between the neighboring IS, stems, usually parallel to them. The longitudinal vessels most commonly terminate round the IS, stems, but sometimes among the initial parts of the IS, stems. The vessel diameters range from 90 to 300 micrometers. The mean value is 155 μm.

The longitudinal vessels sometimes originate not from the IS, but from the ES stems. Likewise, in some cases there is a group of long and thin vessels having all features of the IS, longitudinal branches, but arising from the MCA stem or its cortical branches (fig. 9).

Because of their terminations among the IS, stems, we named them the intersegmental arterioles.

The transverse branches originate from various parts of the IS, stems. Some of these arterioles are very thin, having a caliber of 50 μm only. The largest branches are about 200 μm in size. The mean value is 105 μm.

Distal Portions of the Intracerebral Segments (IS2)

a) Origin

The distal portions, almost as a rule, are continuous with the IS, stems. Four times only we noticed them to arise from the terminal branches of the proximal segments.

b) Course and Relationship to the IS, Stems

The initial part of every IS, stem forms a curve or a real loop with the terminal part of its own IS, stem. In some cases, both curves and loops are present, the former making the border between the IS, and IS, stems, and the latter lying just proximal (fig. 1) or just distal to the border. Curves and loops can be located in the coronal, sagittal, horizontal or oblique plane. Usually obtuse angles are formed between the IS, and IS, stems. Their mean value is 111° (minimum 84°; maximum 156°).

Figure 7. Fan-shaped arrangement of the proximal intracerebral segments. MCA — the right middle cerebral artery. The same specimen as on Figure 6. Medial and slightly rostral view. (11 X).
The distal portions of the intracerebral segments have the opposite direction to the IS\textsubscript{2} stems, i.e., they extend dorsally and medially (fig. 1). In addition, the anterior vessels course also rostrally, and the posterior ones run caudally. The terminal portions of the IS\textsubscript{2} stems and their branches course even more medially, and many of them turn then sharply dorsolaterally. In any case, between the initial and the almost entire distal portion of an IS\textsubscript{2} stem an obtuse angle is formed. Its mean value is 141°, minimum 115° and maximum 160°. Because of such courses, all the IS\textsubscript{2} stems and branches of the same specimen form a broad and concave fan. Its concavity is medially, ventrally and slightly caudally directed. The angle between the most rostral and the most caudal vessel of the fan is 114° (minimum 97°; maximum 128°).

The IS\textsubscript{2} stems can have a regular or tortuous courses. Some vessels form loops.

c) Measurements

The length of every IS\textsubscript{2} stem was measured from its initial up to its distal part, including terminal branches as well. The average length of the lateral vessels is 28 mm (minimum 12 mm; maximum 38 mm). But the value differ within the lateral group itself. Thus, the most rostral vessels have averagely 24 mm in length, those in the middle 33 mm, and the most caudal are 27 mm long. The average length of the medial vessels is 8 mm (minimum 4.5 mm; maximum 13.0 mm).

The diameters of the IS\textsubscript{2} stems were measured just proximal to their terminal divisions (fig. 10). The caliber values are as follows:

<table>
<thead>
<tr>
<th>Diameters of the lateral IS\textsubscript{2} stems</th>
<th>Diameters of the medial IS\textsubscript{2} stems</th>
</tr>
</thead>
<tbody>
<tr>
<td>-mean value 470 μm</td>
<td>-mean value 260 μm</td>
</tr>
<tr>
<td>-minimum 115 μm</td>
<td>-minimum 80 μm</td>
</tr>
<tr>
<td>-maximum 800 μm</td>
<td>-maximum 470 μm</td>
</tr>
</tbody>
</table>

d) Branching

The IS\textsubscript{2} stems give off the collateral and often terminal branches as well.

The collateral branches usually arise at an acute angle, but they can branch off at the right angle too. They may take their origin from any part of an IS\textsubscript{2} stem or its terminal stems. All the collateral branches give off their own branches, which undergo further ramification. So, there are branches of the first, second, third or fourth order. According to their calibers, we divided all the branches into the large, middle-sized and small.
ones. Large branches have calibers of 300 to 350 \( \mu \text{m} \), but sometimes up to 400 \( \mu \text{m} \). Middle-sized branches range in size from 90 to 200 \( \mu \text{m} \), and small ones from 50 to 90 \( \mu \text{m} \). The caliber of the vessels of the fourth order is about 30 \( \mu \text{m} \) only.

The \( IS_2 \) terminal stems are, at the same time, terminal stems of the entire individual perforating arteries. They may arise from the initial (in 25% of cases) or from the distal part of an \( IS_2 \) (75%). Terminal stems of the same \( IS_2 \) are positioned in the sagittal, coronal or oblique plane. They run at first dorsally, medially and slightly rostrally or caudally, and then curve more medially and rostrally, or medially and caudally. Terminal stems, and their branches as well, often have tortuous courses. The loops can be present.

Calibers were measured just distal to the \( IS_2 \) division. The values are as follows:

Diameters of the terminal stems of the lateral vessels

- mean value: 413 \( \mu \text{m} \)
- minimum: 80 \( \mu \text{m} \)
- maximum: 780 \( \mu \text{m} \)

Terminal branches of the lateral vessels are, on average, of 122 \( \mu \text{m} \) smaller than their \( IS_2 \) stems. There are also differences in calibers of the terminal stems arising from the same \( IS_2 \); the average difference is 75 \( \mu \text{m} \).

The mean diameter of the terminal stems of the medial vessels is 195 \( \mu \text{m} \).

Every terminal stem gives off its own collateral and terminal branches, which undergo further ramification. The most distal, i.e., the most dorsal branches of the lateral vessels, have a specific course. Namely, they curve abruptly dorsolaterally. At the same time, their definite branches may change their courses again and turn sharply rostrally or caudally. The length of the definite branches can be up to 20 mm in some cases.

**Ramification Zone**

Ramification zone is the region occupied by all the branches of an arterial vessel. We have measured the longitudinal axis and the greatest diameter of the ramification zone of the terminal stems, proximal and distal intracerebral segments and collateral branches. In all cases the two parameters (axis and diameter) were compared and the following ratios were obtained:

Ramification zone of the terminal stems of the lateral vessels

- mean value: 23.13 mm
- minimum: 13.6 mm
- maximum: 28.33 mm
Hypertensive individuals. In the case of a lateral vessel, we observed in one patient. This is completely in agreement with the observation by guest on April 14, 2017 http://stroke.ahajournals.org/ Downloaded from

Larger diameters, as well as a small formation like a microaneurysm on a lateral vessel, we observed in one hypertensive patient. This is completely in agreement with the observation by guest on April 14, 2017 http://stroke.ahajournals.org/ Downloaded from

- larger
- mean value 30.0:15.5 mm
- minimum 18.0: 6.0 mm
- maximum 40.0:33.0 mm

If a whole lateral intracerebral segment (IS1 + IS2) is taken into account, then the average ratio between the longitudinal axis and the greatest diameter is 37.9:15.5 mm. Finally, the mean ratio for the entire lateral perforating artery (ES + IS) is 41.6 × 15.5 mm.

The ramification zone of the smallest collateral branches has average dimensions of 2.6 × 1.4 mm. The data about the other collateral branches of the first order are shown in the following table:

<table>
<thead>
<tr>
<th>Ramification zone of larger collateral branches of the intracerebral segments</th>
<th>Ramification zone of the IS1 stems of the medial arteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean value</td>
<td>8.9:5.5 mm</td>
</tr>
<tr>
<td>minimum</td>
<td>6.0:2.0 mm</td>
</tr>
<tr>
<td>maximum</td>
<td>18.0:6.0 mm</td>
</tr>
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</table>

Discussion

The knowledge of the cerebral arteries anatomy is always of great significance for neurologists and neuroradiologists dealing with cerebrovascular diseases. The same case is with the perforating branches of the middle cerebral artery.

As can be seen from our results, the perforating arteries are tiny vessels which have very complicated courses and ramification, which, in turn, determine complex hemodynamic conditions in their vascular bed. Curves, loops and tortuous courses of these vessels are their ordinary characteristics as we found them also in young individuals. But these features are more prominent in older individuals, in whom narrower curves, greater number of loops and stronger tortuosity can be noticed. In addition, the perforating vessels of larger diameters, as well as a small formation like microaneurysm on a lateral vessel, we observed in one hypertensive patient. This is completely in agreement with the radiologic findings of some authors in old and hypertensive individuals.

According to Rhodin, caliber value of approximately 300 μm can be used for distinguishing between arteries and arterioles. Taking into account this fact, as well as caliber values obtained in our study, all the intracerebral stems and their branches could be divided into two groups: those belonging to small arteries and the others belonging to arterioles. Small arteries are 300–840 μm in diameter. They comprise the main stems of the lateral perforating arteries, their terminal stems and strong collateral branches, as well as some of the medial perforating arteries. The remaining vessels (most of the medial perforating arteries, some of the terminal and many of the collateral branches) belong to the large (200–300 μm in diameter), medium-sized (90–200 μm) and small arterioles (50–90 μm).

Although these groupings can be useful, they are arbitrary, since only the characteristics of the internal elastic lamina and the number of the smooth muscle cells in the vessel wall are essential for distinguishing between the arteries, and large and small arterioles.

It is well known that the occlusion of the perforating vessels lead to small infarctions (usually called "lacunar infarcts") in the ganglionic region and internal capsule. Fisher distinguishes large infarcts (15–20 mm in size) from small ones (3–4 mm). In general, the size of an ischemic zone, among other things, depends on the caliber of the affected vessel and on the extent of its ramification zone. According to our findings, occlusion of an entire individual lateral perforating artery (ES + IS) would result in an infarct measuring 41.6 × 15.5 mm in average. In an extreme case, with a strong single perforating artery, which gave off three large terminal stems, the measurements of the ramification zone reached the value of 46 × 33 mm. The size of a supplying region is much larger when there is a common stem of the perforating vessels. Thus, in a specimen with a large common stem, which divided into three strong individual perforating arteries, ramification zone measured 53 × 41 mm.

If the entire intracerebral segment (IS1 + IS2) of a lateral artery is involved, an infarction zone of an average of 37.9 × 15.5 mm should be expected. The occlusion of the IS1 only, or of a terminal stem of a lateral vessel, would lead to smaller infarcts: 30.0 × 15.5 mm in average, respectively 23 × 13 mm. Occlusion of one of the medial IS2 stems would give rise to an infarction zone of 11.0 × 4.4 mm in size. The smallest infarcts would be developed by occlusion of the collateral branches: 8.9 × 5.5 mm in size (for larger branches) or 2.6 × 1.4 mm (for the smallest vessels).

The cause of the partial or total occlusion of the perforating arteries can be embolectomy, atheromas, lipohyalinosis and fibrinoid necrosis. Emboli may cause obstruction of vessels of any caliber. Since atheromas usually develop in the perforating arteries ranging from 400 to 900 μm in size, they can be located in the main stems, terminal stems and the largest collateral branches of the perforating arteries. As already mentioned, the ramification zones of these vessels range from 23 × 13 mm up to 37.9 × 15.5 mm. According to Fisher, however, large lacunar infarcts measure up to 20 mm in diameter. This discrepancy could be explained in the following way: first, we measured the longitudinal axis of the ramification zones, which is almost always curved and hence it is longer than the shortest distance from the proximal to the distal border of the ramification zone. On the other hand, Fisher had measured the size of lacunes, that is, of cavities following infarctions, and not the size of infarctions themselves. Second, the occlusion of a perforating artery may cause an infarction zone smaller than the territory of supply of the vessel in-
The caudolateral and caudomedial vessels supply the part of the anterior limb of the internal capsule, as well as the frontal cortex and the caudate nucleus and partially the posterior limb of the caudate nucleus, the body of the caudal part of the lenticular nucleus, and the dorsal portion of the head of the caudate nucleus. The rostromedial perforating arteries supply the rostral portion of the putamen and globus pallidus, the dorsal part of the anterior limb of the internal capsule, as well as the rostral portion of the head of the caudate nucleus. The caudolateral and caudomedial vessels supply the caudal part of the lenticular nucleus, the body of the caudate nucleus and partially the posterior limb of the internal capsule. The lacunar infarcts can be located in the basal ganglia or internal capsule, or in both regions.

The perforating arteries are frequently involved in the ganglionic and capsular hemorrhages. Lipohyalinosis and fibrinoid necrosis usually affect the blood vessels of the basal ganglia or internal capsule, or in both regions. Because of that, small lacunar infarcts will develop as a result of both diseases.

Lipohyalinosis and fibrinoid necrosis usually affect the blood vessels with calibers of less than 200 μm, that is, the most of the medial perforating arteries, the smallest lateral arteries and small terminal and collateral branches. Because of that, small lacunar infarcts will develop as a result of both diseases.

According to some authors, bleeding is due to lipohyalinosis, fibrinoid necrosis and microaneurysms on these vessels. Since the hemorrhages are most often located in the lateral portions of the basal ganglia and internal capsule, it means that usually the lateral vessels are involved. As regards the Charcot's artery ("the artery of cerebral hemorrhage"), it is not a single vessel, but most likely it is one of the lateral perforating arteries.

References
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