Comments, Opinions, and Reviews

Review of the Variability of the Territories of the Major Cerebral Arteries

Albert van der Zwan, MD, and Berend Hillen, MD, PhD

The results of recent model studies indicate that the variability in territorial distribution of the major cerebral arteries may be much greater than has been previously recognized. We review the literature on the cortical and intracerebral territories of the anterior, middle, and posterior cerebral arteries. Although most authors claim that these territories are relatively consistent, the results of their studies show many and considerable discrepancies. The variability described by Beevor has been neither excluded nor completely confirmed, yet somehow the concept of a relatively unchanging pattern of the peripheral cerebral vascularization has gradually settled into the literature. We discuss the considerable variability of the cerebral territories, as well as the discrepancies in investigation techniques, injection materials, and specimen conditions that could be factors producing these dissimilar results. Our study shows that there are no arguments in the literature to negate the variability of the cerebral territories. (Stroke 1991;22:1078-1084)

Since the introduction of computed tomography into neuroradiologic practice, the differential diagnosis of hemodynamic watershed infarction and thromboembolic ischemia is largely based on the location of the visualized infarct. Although a wedge-shaped infarction on empirical grounds suggests a hemodynamic pathogenesis, the primary cause is indicated as thromboembolic when the infarct is not located in one of the well-known border zones. Many templates and diagrams of the territories of the six major cerebral arteries—the anterior (ACA), middle (MCA), and posterior (PCA) cerebral arteries on both sides—provide a guide in making this diagnosis and are based on the concept of a symmetrical and negligibly variable territorial distribution.

This concept is also used in experimental models designed to investigate the hemodynamic behavior of the circle of Willis. In these models, the ratio of the vascular resistance of the six major cerebral arteries is an important parameter, yet the literature provides no accurate data on the in vivo peripheral resistance of these vessels. Thus, the ratio of resistance is estimated, based on the assumption that the peripheral resistance of the six major cerebral arteries is inversely proportional to the brain mass irrigated by each vessel. Because the variability of the territorial distribution is described in the literature as relatively small in contrast to the large variability of the circle of Willis, the ratio of the peripheral resistance of the six major cerebral arteries is considered to be invariant in all models. However, the mathematical model of Hillen et al and statistical analysis of the diameters of various segments of the circle of Willis indicate that within the circle a significant relationship exists between blood flow and vessel size. Considering the large variability of the proximal diameters of the major cerebral arteries, the share of the total cerebral blood flow contributed by each artery is variable as well. These findings suggest that the basic peripheral resistance of the six major cerebral arteries and, consequently, the extent of their territories is as variable as their proximal diameters. This has major consequences not only for model experiments, but also for the neuroradiologic diagnosis of watershed ischemia. If the territorial distribution is as variable as the studies of Hillen et al suggest, the neuroradiologic diagnosis of the watershed ischemia based on the location of the infarct would be even more complex, and the templates of relatively unvarying territories would be most misleading.

Hillen’s results and their implications both for additional model experiments and for neuroradiologic practice demand a review of previous studies on the territorial distribution of the six major cerebral arteries. Because the cortical and intracerebral distributions of the territories are investigated separately in the literature, we discuss the results of relevant studies separately under these two headings.
FIGURE 1. Schematic drawings of the cortical territorial distribution of the anterior (gray), middle (white), and posterior (hatched) cerebral artery according to Duret\textsuperscript{14} (panel A), Foix and Hillemand\textsuperscript{15} (panel B), Robinson\textsuperscript{16} (panel C), and Ferner,\textsuperscript{17} (panel D). Compounds of the maximal (panel E) and minimal (panel F) distribution lines of the middle cerebral artery according to Beevor.\textsuperscript{18}

Cortical Areas of Supply

Figure 1 presents schematic drawings of the cortical territorial distribution of the ACA, MCA, and PCA according to some of the authors discussed below.

Duret\textsuperscript{14} in 1874 was the first to describe the cortical territorial distribution of an unknown number of brains after he sequentially injected colored gelatin into the ACA, MCA, and PCA. He states that the territorial distribution is very constant and that the anastomoses between the territories are too small to be significant. In the distributions he found, the MCA territory reaches the interhemispheric fissure, including the posterior half of the superior parietal gyrus. Using a similar technique in 1878, Charcot\textsuperscript{19} described more or less the same distribution without giving any information about the number of brains examined. In accordance with Duret, he states that the territorial distribution is very constant.

As cited by Beevor\textsuperscript{18} in 1909, the chapter on the cerebral vascularization in Cunningham’s Textbook of Anatomy was originally written by Robinson,\textsuperscript{16} who dissected the cerebral arteries after injecting 12 fixed human bodies with paint through the femoral artery. Robinson’s description of the cerebral territories is considerably different from the distributions found by Duret\textsuperscript{14} and Charcot.\textsuperscript{19} In none of his cases did the MCA reach the interhemispheric fissure. However, he gives no explanation for this discrepancy. Beevor\textsuperscript{18} in 1909 was the first to describe a considerable variability of the cortical distribution of the major cerebral territories. He found noticeably different distributions not only in various specimens, but also in the individual left and right hemisphere. In only 31 of 52 hemispheres did he observe that the MCA territory reached the interhemispheric fissure. Like Heubner,\textsuperscript{20} but contrary to Duret,\textsuperscript{14} he claims that the leptomeningeal anastomoses are large enough to influence significantly the results of sequential injection procedures. For that reason, he developed a simultaneous injection technique to avoid an over-flow of injection material through these leptomeningeal collaterals. Beevor suggests that the constant results described by Duret can be explained by the sequential injection technique inducing this phenomenon of overflow.

In 1923, Foix and Masson,\textsuperscript{21} and in 1925, Foix and Hillemand\textsuperscript{15} described the cortical territories as considerably different from the distribution observed by Duret\textsuperscript{14} and Charcot.\textsuperscript{19} They state that, regardless of the variations in course and division of the cortical branches, the analysis of a large number of dissected brains shows a fixed pattern of territories. However, they give no explanation for the dissimilarities between their results and the distributions described in previous studies, nor do they comment on the variability demonstrated by Beevor.\textsuperscript{18}

During the same time, Shellshear\textsuperscript{22-23} performed his studies on the territorial distribution of the cerebral arteries. He even states that the vascular territories are definitely related to functional cortical areas and that the location of the demarcation lines between the cortical territories is so constant as to enable identification of the gyri and sulci. Furthermore, he claims that the variable demarcation lines found by Beevor are more physiologic lines than anatomic borders and that the location of the boundaries should, therefore, always be confirmed by dissection. In 1927, Shellshear\textsuperscript{23} injected only one fixed brain and then dissected the major vessels. Although the ACA and the MCA were incompletely injected, he claims that the cortical distribution of this case is in keeping with the observations of Duret.\textsuperscript{14} Yet, he provides no precise description of the territorial distribution. He states that the results of other injections he performed show a strong consistency, but data on these injected brains were not available.

Although Shellshear confirms the existence of leptomeningeal anastomoses, he denies that they play an important functional role.

In 1953, Meyer\textsuperscript{24} described the pathologic findings in 30 brains of young children who died of hypoxic brain damage as a result of circulatory insufficiency. He assumed that the infarctions he observed were located in the territorial demarcation zones. In none
of the brains did he find the border zone between the MCA territory and the other major territories extending to the interhemispheric fissure. He concludes that the locations of the demarcation lines are only slightly variable but does not discuss the evident discrepancies between his observations and those of Duret.14

Vander Eecken and Adams25 in 1953 and Vander Eecken26 in 1959 described a territorial distribution similar to the drawings of Foix and Hillemand.15 These extensive studies initiated a large series of investigations on the leptomeningeal anastomoses. However, by that time, the relatively invariant pattern of the territorial distribution had been generally accepted, and any discussion on its large variability ceased to exist in the literature.

It was more recently that Stephens and Stilwell,27 Waddington,28 Lang,29 and Ferner17 provided different schematic drawings and photographs of distributions after sequential injection and gross dissection of the cerebral arteries. Their descriptions of the cerebral territories show various inconsistencies with previous findings. For instance, they did not find the MCA reaching the interhemispheric fissure in their studies. Yet, none of these authors sufficiently explains the discrepancies between their results and previous findings.

**Intracerebral Areas of Supply**

Because our interest is focused on the areas of supply of the ACA, MCA, and PCA, we exclusively include the results of studies performed on the demarcation lines between these vessels. Therefore, the areas of interest are the white matter, the head of the nucleus caudatus, the putamen, and the globus pallidus. In general, the opinions on the territorial distribution of the internal structures show the same historic pattern as those on the cortical distribution. Although early authors still discuss the different territorial distributions they found, later authors describe a generally accepted, relatively invariant vascularization pattern. In the following sections, we will survey the generally accepted results of more recent studies and discuss the variations described by earlier authors. Figure 2 depicts the locations of the intracerebral boundaries described in five different studies.

**White Matter**

Table 1 summarizes studies on the territorial distribution of the ACA and MCA in the anterior limb of the internal capsule. According to most authors, the anterior limb of the internal capsule is invariantly supplied by the striate arteries of both the ACA (anterior part) and MCA (posterior part).15,27,33,34 However, Beevor18 observed in two of 41 hemispheres that the anterior limb was exclusively supplied by the ACA or MCA. In the rest of his cases, he found many variations of the demarcation line between the ACA and MCA in the anterior limb. Alexander22 also reports a variable territorial distribution of the anterior limb. Information about the location of the border zones between the ACA, MCA, and PCA in the remaining white matter is sparse. In most studies, only schematic drawings show straight demarcation lines extending from the cortical border zones to the territories in the deep intracerebral regions. Only Beevor18 extensively describes the territorial distribution in the optic radiation. In 15 brains, he found a variable supply corresponding with the territorial distribution of the occipital cortex. In the case in which the cortical territory of the MCA extends to the occipital pole, the vascularization of the optic radiation is principally from the MCA, and the intracerebral border zone between the MCA and PCA is located more posteriorly and medially.

**Head of the Nucleus Caudatus**

Table 2 summarizes studies on the territorial distribution of major cerebral arteries in the head of the nucleus caudatus. According to most authors, the
Table 1. Studies on the Territorial Distribution of the Anterior and Middle Cerebral Arteries in the Anterior Limb of the Internal Capsule

<table>
<thead>
<tr>
<th>Author</th>
<th>ACA</th>
<th>MCA</th>
<th>Method</th>
<th>No. of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heubner</td>
<td>+</td>
<td>+</td>
<td>Sequential injection, dissection</td>
<td>17</td>
</tr>
<tr>
<td>Kolisko</td>
<td>+</td>
<td>+</td>
<td>Sequential injection, dissection</td>
<td>1</td>
</tr>
<tr>
<td>Beevor</td>
<td>Ant-Inf, variable</td>
<td>Post-Sup, variable</td>
<td>Simultaneous injection, slices</td>
<td>41</td>
</tr>
<tr>
<td>Foix and Hillemand</td>
<td>Anterior</td>
<td>Rest</td>
<td>Sequential injection, pathologic examination, x-ray</td>
<td>Unknown</td>
</tr>
<tr>
<td>Alexander</td>
<td>Anterior</td>
<td>Rest</td>
<td>Sequential injection, dissection</td>
<td>13</td>
</tr>
<tr>
<td>Kaplan and Ford</td>
<td>Anterior</td>
<td>Rest</td>
<td>Total injection, dissection</td>
<td>20</td>
</tr>
<tr>
<td>Stephens and Stilwell</td>
<td>Anterior</td>
<td>Rest</td>
<td>Total injection, x-ray</td>
<td>Unknown</td>
</tr>
</tbody>
</table>

ACA, anterior cerebral artery; MCA, middle cerebral artery; +, artery participates in the supply; Ant-Inf, anterior and inferior; Post-Sup, posterior and superior.

A variable territorial distribution is reported by Beevor. In 22 of 39 hemispheres, the head of the nucleus caudatus was supplied in equal parts by the ACA (inferior part) and MCA (superior part). In eight hemispheres, the head was completely supplied by the ACA. In two hemispheres, the MCA was the only source of supply. Alexander in 1942 also reported a variable distribution of the vascularization of the nucleus caudatus. In only 60% of his material, the ACA supplied the anterior part of the head of the nucleus caudatus.

Table 2. Studies on the Territorial Distribution of the Anterior, Middle, and Posterior Cerebral Arteries in the Head of the Nucleus Caudatus

<table>
<thead>
<tr>
<th>Author</th>
<th>ACA</th>
<th>MCA</th>
<th>PCA</th>
<th>Method</th>
<th>No. of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duret</td>
<td>+</td>
<td>-</td>
<td>+</td>
<td>Sequential injection, dissection</td>
<td>Unknown</td>
</tr>
<tr>
<td>Heubner</td>
<td>Ant-Lat</td>
<td>Post-Med</td>
<td>-</td>
<td>Sequential injection, dissection</td>
<td>17</td>
</tr>
<tr>
<td>Beevor</td>
<td>Variable</td>
<td>Variable</td>
<td>Variable</td>
<td>Simultaneous injection, slices</td>
<td>39</td>
</tr>
<tr>
<td>Alexander</td>
<td>Ant-Med, variable</td>
<td>Variable</td>
<td>-</td>
<td>Sequential injection, dissection</td>
<td>13</td>
</tr>
<tr>
<td>Lazorthes, Gouzé, Salamon</td>
<td>Medial</td>
<td>Lateral</td>
<td>-</td>
<td>Sequential injection, x-ray</td>
<td>35</td>
</tr>
<tr>
<td>Zülch</td>
<td>Anterior</td>
<td>Inferior</td>
<td>-</td>
<td>Pathologic examination</td>
<td>1</td>
</tr>
<tr>
<td>Herman, Ostrowski, Gurdjian</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>Sequential injection, dissection</td>
<td>20</td>
</tr>
<tr>
<td>Kaplan and Ford</td>
<td>Medial</td>
<td>Lateral</td>
<td>-</td>
<td>Sequential injection, x-ray</td>
<td>Unknown</td>
</tr>
<tr>
<td>Stephens and Stilwell</td>
<td>Ant-Inf</td>
<td>Ant-Sup</td>
<td>-</td>
<td>Total injection, x-ray</td>
<td>38</td>
</tr>
<tr>
<td>De Reuck</td>
<td>Ant-Inf</td>
<td>Ant-Sup</td>
<td>-</td>
<td>Sequential injection, x-ray</td>
<td>26</td>
</tr>
</tbody>
</table>

ACA, anterior cerebral artery; MCA, middle cerebral artery; PCA, posterior cerebral artery; +, artery participates in the supply; -, artery does not participate in the supply; Ant, anterior; Lat, lateral; Post, posterior; Med, medial; Inf, inferior; Sup, superior.
that the anterior part is supplied by the ACA. Although Duret\textsuperscript{14} claims that the putamen is exclusively supplied by the MCA, Beevor\textsuperscript{18} confirms the finding of Kolisko in 38 of 47 hemispheres in varying degrees. Only in nine of his cases was the putamen not supplied by the ACA. In six of nine hemispheres Alexander injected,\textsuperscript{32} the ACA participated in the vascularization of the putamen.

**Globus Pallidus**

Table 4 summarizes studies on the territorial distribution of the ACA and MCA in the lateral part of the globus pallidus. Although the anterior choroid artery and the striate arteries of the MCA are generally considered as the only sources of supply of the globus pallidus, some authors report that the globus pallidus is partly supplied by the ACA and that, therefore, a demarcation line between the ACA and MCA is to be found in this nucleus.\textsuperscript{15,18,20,32} Foix and Hillemand\textsuperscript{15} do not mention any variability in their study, and they indicate that the ACA supplies the anterior medial part of the globus pallidus. In 12 of 26 hemispheres injected in several injection classes, Beevor\textsuperscript{18} observed that the lateral part was supplied by both the ACA and MCA in varying degrees. In these hemispheres, the ACA territory was located anteriorly to the area of the MCA. In the remainder, this nucleus was exclusively supplied by the ACA (three cases) or MCA (11 cases). Alexander\textsuperscript{32} reports that in six of nine hemispheres he investigated, the anterior ventral part of the lateral globus pallidus was supplied by the ACA in varying degrees.

**Discussion**

Although we do not claim that this review includes all papers on the territorial distribution of the six major cerebral arteries, we feel that the selected papers are the most representative studies on this subject. Numerous standard atlases and textbooks show many schematic drawings of "normal" territorial distribution.\textsuperscript{1-5,37,38} Most of these distributions are compilations of the results of previous studies. For instance, the location of the ACA–PCA boundary at the superior surface of the hemisphere is described in the precuneal lobe,\textsuperscript{5} in the parieto-occipital sulcus,\textsuperscript{2,4,37} and also more posteriorly halfway between the latter and the occipital pole.\textsuperscript{38} Yet, in none of these cited descriptions has the MCA reached the interhemispheric fissure according to the distribution of Duret.\textsuperscript{14} It is, therefore, remarkable that even extensive textbooks provide only sparse information of this variability. Because references to the origin on the templates or to the investigation technique are usually lacking, our survey excludes these works. Damasio\textsuperscript{4} though frequently cited in the

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**Table 3. Studies on the Territorial Distribution of the Anterior and Middle Cerebral Arteries in the Putamen**

<table>
<thead>
<tr>
<th>Author</th>
<th>ACA</th>
<th>MCA</th>
<th>Method</th>
<th>No. of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duret\textsuperscript{14}</td>
<td>−</td>
<td>+</td>
<td>Sequential injection, dissection</td>
<td>Unknown</td>
</tr>
<tr>
<td>Kolisko\textsuperscript{31}</td>
<td>Anterior</td>
<td>Posterior</td>
<td>Sequential injection, dissection</td>
<td>1</td>
</tr>
<tr>
<td>Beevor\textsuperscript{18}</td>
<td>Ant-Inf, variable</td>
<td>Post-Sup, variable</td>
<td>Simultaneous injection, slices</td>
<td>47</td>
</tr>
<tr>
<td>Alexander\textsuperscript{32}</td>
<td>Anterior, variable</td>
<td>Posterior, variable</td>
<td>Sequential injection, dissection</td>
<td>9</td>
</tr>
<tr>
<td>Lazorthes, Gouazé, Salamon\textsuperscript{18}</td>
<td>Anterior</td>
<td>Posterior</td>
<td>Sequential injection, x-ray</td>
<td>35</td>
</tr>
<tr>
<td>Kaplan and Ford\textsuperscript{34}</td>
<td>Anterior</td>
<td>Posterior</td>
<td>Sequential injection, dissection</td>
<td>Unknown</td>
</tr>
<tr>
<td>Stephens and Stiwell\textsuperscript{27}</td>
<td>Ant-Inf</td>
<td>Post-Sup</td>
<td>Total injection, dissection, x-ray</td>
<td>38</td>
</tr>
</tbody>
</table>

ACA, anterior cerebral artery; MCA, middle cerebral artery; +, artery participates in the supply; −, artery does not participate in the supply; Ant-Inf, anterior and inferior; Post-Sup, posterior and superior.

**Table 4. Studies on the Territorial Distribution of the Anterior and Middle Cerebral Arteries in the Lateral Part of the Globus Pallidus**

<table>
<thead>
<tr>
<th>Author</th>
<th>ACA</th>
<th>MCA</th>
<th>Method</th>
<th>No. of specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heubner\textsuperscript{20}</td>
<td>+</td>
<td>+</td>
<td>Sequential injection, dissection</td>
<td>17</td>
</tr>
<tr>
<td>Beevor\textsuperscript{18}</td>
<td>Anterior, variable</td>
<td>Posterior, variable</td>
<td>Simultaneous injection, slices</td>
<td>26</td>
</tr>
<tr>
<td>Fox and Hillemand\textsuperscript{15}</td>
<td>Ant-Med</td>
<td>Post-Inf-Lat</td>
<td>Sequential injection, pathologic examination, x-ray</td>
<td>Unknown</td>
</tr>
<tr>
<td>Alexander\textsuperscript{32}</td>
<td>Anterior, variable</td>
<td>Posterior, variable</td>
<td>Sequential injection, dissection</td>
<td>9</td>
</tr>
</tbody>
</table>

ACA, anterior cerebral artery; MCA, middle cerebral artery; +, artery participates in the supply; Ant-Med, anterior and medial; Post-Inf-Lat, posterior, inferior, and lateral.
literature, also is not included in the listing because she refers to investigations performed by others that are discussed in this review.28,35

Although both in model experiments and in neuroradiologic practice the concept of a relatively invariant territorial distribution is generally accepted, this review demonstrates that there are many discrepancies among the distributions previously described. In our opinion, several factors may have led to these inconsistencies.

First, the variability of the hemispheric territorial distribution is much larger than has been considered up to now. Also, intrindividually, the territorial patterns in both hemispheres may show a considerable asymmetry, such as Beevor already demonstrated in some of his cases.18 In addition, the individual territorial distribution may change in time as a result of altering hemodynamic circumstances. As the results of Hillen's studies suggest,11-13 this interindividual, intraindividual, and time-related variability may be an analogue to the well-known variability of the circle of Willis, making it difficult to define a most common territorial distribution.

Second, various authors have used different investigation techniques, such as x-ray after injection of radiopaque substances, 15, 27, 34-36 injection of colored dyes with or without dissection, 14-23, 25, 26, 28, 29, 32, 33 or pathologic examination. 15, 24, 30 Most authors who injected the cerebral arteries used different, nonstandardized injection techniques. Nine authors injected only one artery at the time, considering the errors arising from overflow of injection material through anastomosing arteries at minimal. 14, 15, 19, 21, 32-36 Only Beevor18 simultaneously injected the cerebral arteries with different colored dyes to avoid overflow through these anastomoses. 18 Others investigated the cerebral territories after injecting all arteries with the same dye. 16, 27 However, with this technique, the distinction of the intracerebral territories seems to be less accurate. 27 Furthermore, many authors used numerous different injection materials such as ink, 18, 20, 33 gelatin, 14, 18, 20, 22, 23, 27, 32, 33 latex, 25, 26 barium sulfate or other radiopaque substances, 27, 34-36 olive oil, 31 or acrylic plastic. 27 The physical properties of these injected substances, such as viscosity and hardening time, have a major influence on the filling of the arterial tree and, consequently, on the accuracy of the investigation. 39 Therefore, the different investigation techniques and various injection materials used in previous studies may yield the inconsistent results demonstrated in this review.

Third, only a few authors give sparse information on the condition of the specimens they investigated in their studies. The presence of fixative, obstructing blood clots, or both has a detrimental effect on the filling of the arterial tree. 39 Therefore, studies performed under different, nonstandardized conditions may have dissimilar results.

This review demonstrates that the concept of a relatively small variability of the cerebral territories is based on insufficient data from the literature and that its use should therefore be questioned. Hillen's results11-13 and the lack of clear data in the literature demand a reinvestigation of the territories of the six major cerebral arteries. A quantitative study, performed under standardized conditions, will be useful for both model experiments and clinical investigation of the cerebral circulation, providing more detailed information about the variability of the cerebral territorial distribution.

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