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REVIEW ARTICLE

Embryological Lateral Striate Artery Variants

Revised Concept of Recurrent Artery of Heubner, the Perforators to the Anterior Perforated Substance and Middle Cerebral Artery Variants

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Abstract

Purpose The anterior perforating arteries are a group of arteries that enter the brain through the anterior perforated substance (APS). Because the lenticulostriate artery, the recurrent artery of Heubner (RAH) and the perforators from A1 of anterior cerebral artery (ACA) penetrate the APS and supply the basal ganglia, these arteries can be considered as having a common embryological origin.

Results During development, the lateral striate arteries are divided from the lateral olfactory artery and divided into the RAH and middle cerebral artery (MCA). The RAH is a fascinating artery for its early development and variations of origin and course. The MCA has also several variations, such as the duplicated MCA, accessory MCA, and fenestration.

Conclusion We provide a review of embryologic development and anatomical variations of the RAH, the perforators to the APS and MCA as a group of the lateral striate artery.

Keywords Lateral striate artery · Lateral olfactory artery · Anterior perforated substance · Telencephalon · Embryology

Abbreviations

ACA	Anterior cerebral artery
AChA	Anterior choroidal artery
APS	Anterior perforated substance
DMSA	Distal medial striate artery
FPA	Frontopolar artery
ICA	Internal carotid artery
MCA	Middle cerebral artery
mFBA	Medial frontobasal artery
PMSA	Proximal medial striate artery
Pu	Putamen
POA	Primitive olfactory artery
RAH	Recurrent artery of Heubner

Introduction

The anterior perforating arteries are a group of arteries that enter the brain through the anterior perforated substance (APS) [1]. These arteries arise from the internal carotid, middle and anterior cerebral and the anterior choroidal arteries. Branches of the internal carotid and anterior choroidal artery enter the posterior half of the central portion of the APS. The lenticulostriate branches, which arise from the M1 and M2 segments, enter the middle and posterior portions of the lateral half of the APS. The A1 segment gives rise to branches which enter the medial half of the APS above the optic nerve and chiasm. The recurrent artery of Heubner (RAH) sends branches into the anterior two thirds of the full mediolateral extent of the APS.

The site of penetration in the mediolateral direction is determined by a line drawn posteriorly along the olfactory tract. The site of penetration of each group of arteries is also determined in an anteroposterior direction, by dividing the APS into anterior, middle, and posterior zones, and determining which zone the groups penetrated [1]. In other words, the perforators to the APS are orderly parallel re-

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gardless of its artery of origin, from medial to lateral (RAH, A1 and middle cerebral artery, MCA).

In the literature, the description of the perforating arteries is divided into sections based on the artery of origin and discussed independently. From a embryological point of view, the MCA is a branch of the ACA and belongs to the group of lateral striate arteries, and the RAH and the perforator from A1 also develop from the lateral striate arteries [2]. The fact that the perforators penetrating the APS share its territories and variations prompted us to review this embryological lateral striate artery group to propose a concept as to their common embryological origin.

Telencephalon and Blood Supply

The prosencephalon (forebrain), the mesencephalon (midbrain), and the rhombencephalon (hindbrain) are three primary brain vesicles during the early development of the nervous system. The prosencephalon divides into the telencephalon and the diencephalon. The two major telencephalic subdivisions are the pallium (the roof) and the subpallium (the base). The pallium gives rise to the cerebral cortex, whereas the basal ganglia derive from the subpallium. The cerebral hemispheres expand greatly during the early months of gestation [3].

The first vessels penetrate the telencephalon (basal ganglia or subpallium) in the seventh week, forming a subventricular plexus at about 12 weeks of gestation [4]. At 16 weeks of gestation, the anterior cerebral artery (ACA), MCA, and posterior cerebral arteries are well established [5]. The striate arteries penetrate the brain via the APS and supply the basal ganglia and internal capsule. At 24 weeks of gestation, a large part of the basal ganglia and internal capsule is supplied by a prominent RAH arising from the ACA [6]. Gradually, the area supplied by MCA becomes predominant when compared with the territories supplied by the ACA and posterior cerebral arteries [7]. By 32–34 weeks of gestation, the cerebral cortex acquires its complex gyral pattern with an increased vascular supply.

Development of ACA and MCA

Embryologically, the developing telencephalon is supplied by the ICA, which comprises the cranial and caudal branches [2]. The terminal end of the cranial division of the carotid artery constitutes the primitive olfactory artery (POA). The POA, from which the ACA eventually develops, has the medial and lateral olfactory arteries. The medial olfactory artery joins with the artery from the contralateral side, in the mid-line region by the future anterior communicating artery. The larger derivatives (lateral olfactory artery) of the POA extend laterally, partially entering the medial part of the APS, for supplying the basal ganglia. The lateral olfactory artery divides into the lateral striate artery and primitive anterior choroidal artery (AchA). Just distal to the primitive AchA, multiple plexiform arterial branches appear, which later develop into lateral striate arteries by fusion and regression [5]. A group of embryological lateral striate arteries supply the growing cerebral hemisphere and the basal ganglia, which later become the perforator to the APS (including the RAH) and MCA. Embryologically, the MCA can be regarded as a branch of ACA ([8]; Fig. 1). Finally, at the 40 mm stage of the embryo, the MCA attains the approximate adult configuration [5].

Distal/Proximal Medial Striate Arteries of ACA

Perforating arteries from the internal carotid artery (ICA), ACA, and MCA enter the brain parenchyma through the APS. The perforating arteries of ACA are called medial striate arteries in the literature. Yaşargil subdivided the medial striate arteries into the distal medial striate artery (DMSA) and proximal medial striate artery (PMSA) [9]. The RAH is the DMSA and is distinguished from the PMSA (an average of 8 perforators, range 2–15 [10]) originating from the proximal A1. In some cases, both the PMSA and RAH have a common origin from the ACA [9], this variation suggesting the common embryological origin of the PMSA and RAH. They supply the anterior and inferior parts of the head of the caudate nucleus, the anterior limb of the internal capsule, the adjacent parts of the putamen (Pu) and the globus pallidus, the caudal rectus gyrus, the subcallosal gyrus, and the medial part of the anterior commissure.

Recurrent Artery of Heubner

In the literature many discussions exist about the origin and courses of recurrent artery of Heubner (RAH), which was first described by Heubner in 1872. The RAH exists as single or multiple trunks originating from the ACA at the level of the A1–A2 junction and courses along the horizontal portion (A1) of the ACA. The RAH most frequently penetrates the brain parenchyma at the level of the lateral part of the APS or the medial portion of the Sylvian fissure. Abbie stated that the RAH is the survivor of the anastomoses over and around the paleo-olfactorium and obtains most of its blood from the ACA but retains its old connection with the MCA [8]. These two arteries (MCA and RAH), with the same embryologic origin (i.e., embryological lateral striate artery) (Fig. 1), may supply the same parenchymal territory (the medial Pu, the caudate head, and part of the an-

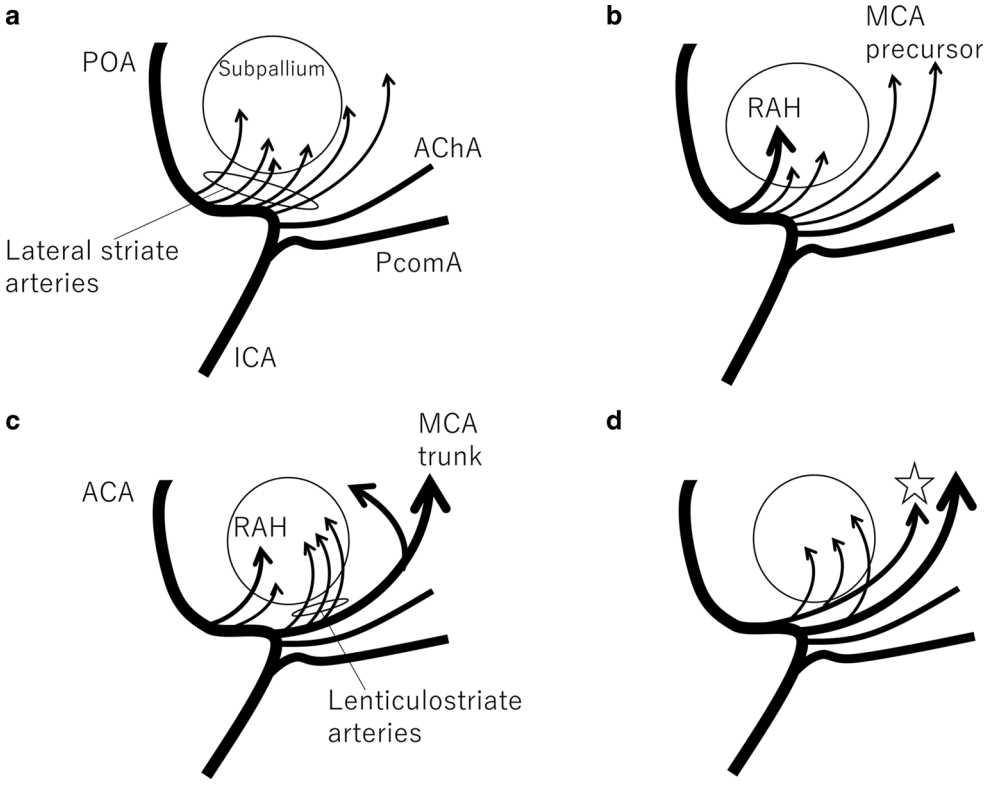

Fig. 1 Schematic representation of the formation of the anterior cerebral artery (ACA), recurrent artery of Huebner (RAH) and middle cerebral artery (MCA). **a** The terminal end of the ICA cranial branch constitutes the primitive olfactory artery (POA). Multiple plexiform arterial twigs appear just distal to the anterior choroidal artery (AchA) and evolve into the embryological lateral striate arteries. **b** A large part of the basal ganglia and internal capsule is supplied by prominent RAH at 24 weeks of gestation. MCA precursors also develop from embryological lateral striate arteries. **c** Adult configuration of cerebral arteries of anterior circulation. The basal ganglia are supplied mainly by the RAH (distal medial striate artery), proximal medial striate arteries (perforators of A1), and lenticulostriate arteries from the MCA trunk. **d** The star indicates a lateral striate artery variant (RAH with cortical supply, or accessory MCA with lenticulostriate arteries). *AChA* anterior choroidal artery, *PcomA* posterior communicating artery, *ICA* internal carotid artery

terior limb of the internal capsule) [11, 12]. A reciprocal relationship between two arteries during the embryological development well explains variations in the brain territory supplied by the RAH [2]. The presence of extracerebral and intracerebral anastomoses between the perforating branches of the RAH and of the MCA (the medial lenticulostriate artery is the most frequently involved) seems to support Abbie's opinion and the incidence is about 10% [13–15].

The number of the RAHs is variable. Vasović et al. reported from dissections in 94 human fetal brains a single RAH in 71.6%, double RAH in 25.1%, and triple RAH in 3.3% [16]. Matsuda et al. investigated 714 hemispheres and they found a single RAH in 96.2%, double in 2.4%, and triple 0.14% [17]. The origin of the RAH is also variable, but the most frequent point of origin was the A1–A2 junction, in about half of patients [18]. There were other variations of the origin of the RAH, the common trunk with the medial frontobasal artery (mFBA) or frontopolar artery (FPA), [19] the common trunk of the orbitofrontal artery [17], the medial frontobasal artery [16], the medial orbitofrontal artery [19], or contralateral A1 or A2 [16].

The RAH can branch off cortical arteries to the frontal lobe. Tao et al. reported there were branches from the RAH suppling the cortex in the medial portion of the orbital part of the frontal gyrus [19]. Maga et al. found that the supraoptic nucleus, the terminal lamina, and the optic chiasm were supplied by RAH branches [15]. The variation in the number and origins of the RAH led to confusion and misinterpretation about which branch is the cortical artery of the ACA or RAH. Variations in origin and number depend on which anastomotic channels remain and regress during development [8]. These facts emphasize that the RAH and some of the ACA cortical arteries (mFBA and FPA) are embryologically the same in origin and show the consequence of the persistence of embryological lateral striate arteries.

MCA Variations

The MCA normally arises from the ICA as a single artery. The MCA has several variations, such as the accessory

MCA, duplicated MCA, and fenestration. During development, the failure of fusion of the lateral striate arteries may result in two MCA trunks. If the smaller trunk arises distal to the main MCA, it is defined as an accessory MCA. Conversely, if the smaller trunk arises proximal to the main MCA, it is defined as duplicated MCA [20, 21]. The incidence of an accessory MCA in angiographic and anatomical studies is reported to be 0.3–4.0% and that of a duplicated MCA 0.2–2.9% [22].

Komiyama et al. suggested that the development of an accessory and/or duplicated MCA is an anomalous early ramification of the early branches of the MCA [22]. Besides the dual origin of the MCA (accessory MCA and duplicated MCA), MCA fenestration is rare. In MCA fenestration, the MCA originates as a single trunk, but there is the presence of luminal division of the vessel into two separate and parallel channels, which rejoin distally. Gailloud et al. hypothesized that MCA fenestration results when the early branching of the temporopolar artery causes failure in fusion of the primitive network of the MCA [23]. Although the consensus opinion about these MCA variations has not been presented to date, accessory MCAs, duplicated MCAs, and MCA fenestration may form due to the failure in fusion of the primitive arterial network (group of lateral striate arteries).

Accessory MCA and RAH

An accessory MCA is defined as a vessel that originates between the A1 and the proximal A2 segments of the ACA, reaches the Sylvian fissure, and feeds the territory of the MCA [22, 24, 25]. There are several explanations regarding the embryological origins of an accessory MCA. Takahashi et al. considered the accessory MCA to be a persistent embryological channel formed from anastomotic vessels between the MCA and ACA at the level of the tuberculum olfactorium [24]. There are abundant anastomoses on the cortical surface between the MCA and an accessory MCA [26]. Handa et al. supported by other authors, considered the accessory MCA as a hypertrophic RAH extending Abbie's theory [8] that the RAH is a remnant of anastomotic channels between the ACA and MCA [24, 27, 28]. Teal et al. disagreed on the basis that (1) perforating arteries only occasionally arose from an accessory MCA. (2) An RAH and an accessory MCA can be simultaneously present. (3) The RAH enters the APS medial to lenticulostriate arteries while an accessory MCA courses lateral to them. On the other hand, Tran-Dinh et al. discussed the finding that the simultaneous presence of an RAH and an accessory MCA may be in fact a duplication of the hypertrophic RAH [28]. The variations in accessory MCAs express the embryological origins of the MCA from a group of vessels with similar potentials in the early stages of development, i.e. lateral striate arteries.

It is generally accepted that an accessory MCA has perforating branches to the APS [25, 28] (Fig. 2). Marinković et al. also reported cases in which an RAH originated from an accessory MCA (4%) [12]. Matsuda et al. reported brain specimens in a case where RAHs originated from accessory MCAs [17] but they misinterpreted two perforators branching off an accessory MCA as double RAHs. In a radiological study, Kang et al. also reported a similar case in which the RAH originated from an accessory MCA [29]. In contrast, the absence of any RAH in a hemisphere is exceedingly rare (2%) by previous reports [18]. These facts help us to understand the embryological considerations of the accessory MCA. As Lasjaunias et al. explained [2], an

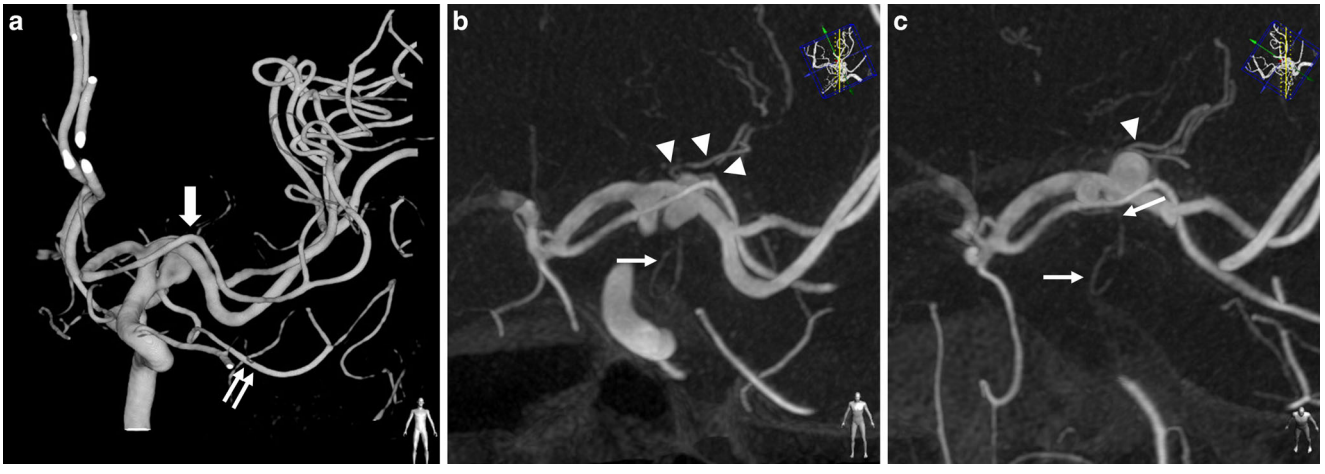

Fig. 2 A case with accessary MCA and duplicated MCA. **a** Left internal carotid artery (ICA) (3D rotational angiography). *Arrow* indicates accessary MCA originating from left A2, and *double arrow* indicates duplicated MCA. The unruptured aneurysm located at the bifurcation of ICA and duplicated MCA. **b**, **c** Reconstruction images from 3D rotational angiography. *Arrowheads* indicate lenticulostriate arteries from accessory MCA, and *arrows* indicate orbitofrontal artery from accessary MCA

embryological analysis confirms that an accessory MCA is the same as a hypertrophic RAH with a cortical supply (Fig. 1d).

Lenticulostriate Artery

Perforating arteries of the MCA usually originate from the M1 segment. Lenticulostriate arteries can be classified into two groups: medial and lateral lenticulostriate arteries [30]. The lenticulostriate arteries usually supply the superior parts of the head and the body of the caudate nucleus, the lateral segment of the globus pallidus, the Pu, and the dorsal half of the internal capsule. The medial portions of the caudate head, Pu and internal capsule, and lateral border of the external segment of the globus pallidus, are supplied by the medial lenticulostriate arteries. Lateral lenticulostriate arteries supply most of the lateral Pu and remaining caudate head (Cd) including the internal capsule between them. Feekes et al. investigated the microvascular territories of lenticulostriate artery, the RAH and AchA in perfusion-fixed human brains, and concluded that these three arteries supply distinct territories of the basal ganglia with minimal overlap and sparse anastomoses between major penetrating vessels and individual territories are spatially consistent across brains [31]; however, the lenticulostriate artery has a variety of origins (Fig. 3). Kang et al. reviewed 3D reconstructed rotational angiography images showing that lenticulostriate arteries from the ACA, which are identical to PMSAs in this paper, were observed in 70%. They found lenticulostriate arteries originating from accessory MCA in all 11 cases except 1 and that they arise anywhere along the accessory MCAs [29]. Supply to the basal ganglia seems to maintain a balance between the medial and lateral lenticulostriate arteries: when lateral lenticulostriate arteries are prominent, there is less contribution from medial lenticulostriate arteries and vice versa.

The lenticulostriate artery has several patterns of its origins, mainly from the MCA, accessory MCA, A1, and RAH. To summarize, the lenticulostriate artery can originate from any branch of the embryological lateral striate artery variants. The topographical map of the APS is predetermined during embryogenesis, from where the perforators (lenticulostriate artery, RAH, and PMSA) branched depending on the pattern of regression and fusion of lateral striate arteries.

Conclusion

Since the RAH (DMSA), PMSA and lenticulostriate arteries are all perforators to the APS and share the same embryogenetic origin, their territories and anatomical variations are related to each other. The RAH, PMSA, lenticulostriate arteries, and MCA variations (accessory MCA, duplicated MCA and MCA fenestration) are all derivatives from embryological lateral striate arteries, and these can all be regarded as possible variants of lateral striate arteries. Embryologically, the accessory MCA from A1 can be regarded as a hypertrophic RAH with cortical supply. There are multiple and extensive variations of origin, number, anastomosis, and absence in the lateral striate artery group, and many patterns of variations are possible and differ individually.

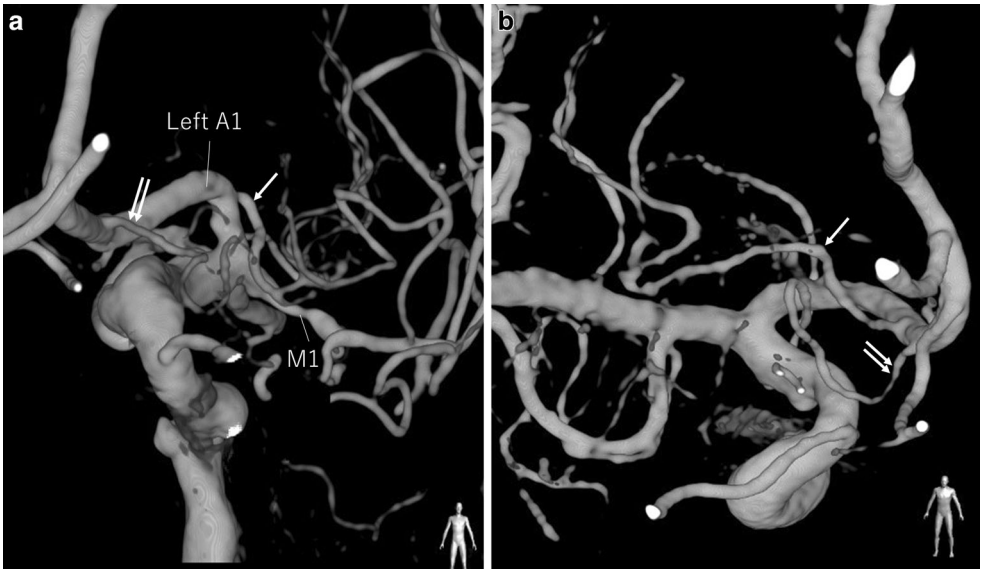

Fig. 3 Two cases with lenticulostriate artery of uncommon origin. **a** Lenticulostriate artery originates from the left proximal A1. *Arrow* lenticulostriate artery, *double arrow* recurrent artery of Heubner. **b** This case has a recurrent artery of Heubner (*arrow*) originating from the distal A1 and lenticulostriate arteries from the RAH. *Double arrow* indicates small cortical branches from the distal A1, not RAH

Compliance with ethical guidelines

Conflict of interest T. Ota and M. Komiyama declare that they have no competing interests.

Ethical standards All procedures performed in studies involving human participants or on human tissue were in accordance with the ethical standards of the institutional and/or national research committee and with the 1975 Helsinki declaration and its later amendments or comparable ethical standards. Informed consent was obtained from all individual participants included in the study.

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